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Message from the Incoming NACA President

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In the last year, we saw several publications highlighting the burden of disease attributable to air pollution globally and in South Africa. The Intergovernmental Panel on Climate Change also published their sixth assessment report, confirming that global mean temperatures will exceed 1.5 degrees Celsius in all the shared socioeconomic pathways. In the face of these challenges, the need for a platform that can foster an environment of innovation that can drive local solutions is paramount. This is exactly what the National Association for Clean Air has been aiming to do for over 50 years.

The world is slowly recovering from COVID-19, and in 2022, restrictions limited the number of face-to-face interactions in the community. We have, however, expanded our virtual footprint by enhancing the Schools Outreach program on the NACA website, a 50-minute documentary on how we address air quality through science is continuing to draw views (https://youtu.be/tIghFFn22Nc), and several virtual seminars.

The annual conference was held in Kempton Park, Gauteng, between 5 and 7 October 2022. A joint multi-stakeholder workshop in collaboration with DFFE and a technical session chaired by the GCRF Mine Dust and Health Network was part of the program on 5 October. The conference hosted two keynote presentations, one from Prof Peter Adams from Carnegie Mellon University in the USA on "Reduced-complexity air quality models: tools for nimble policy assessment", and another from Mr Ian Sampson from Shepstone & Wylie with the title "The time is now to find each other to control pollution" and another from Dr Mantagu Murray of the NOVA institute with the title "Air quality and quality of life". The conference also saw 18 peer-reviewed papers, an ESKOM workshop titled "Taking Eskom JET forward - Eskom repowering and repurposing project", a poster session, and a 3-minute talk session. The complete proceedings are available on the NACA website. The post-conference questionnaire showed 48% representation from academia, 39% representation from industry, 10% from government, and 3% from the broader society. The feedback showed that the community thought the conference was engaging and applicable (77% agreed), was happy with the balance between academic and applied topics (77% agreed), and that the exhibitions were interesting and engaging (90%). The scientific conference committee chaired by Dr Anzel de Lange will aim to host another successful conference again in 2023.

The Clean Air Journal remains the most valuable resource of the NACA community. It continues to provide a free, open access, option for researchers to publish their work. The focus has expanded to include the whole of Africa. NACA will continue to work towards supporting the independent editorial board and the CAJ to expand their influence in 2023.

The NACA council calls on government, academia, industry and society to continue to work together towards a healthy and sustainable future in 2023.

Roelof Burger
Incoming NACA President

Erratum
The use of dirty fuels by low-income households on the South African Highveld

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Commentary
The time is now to find each other to control pollution

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The paradox of pollution and the law

Environmental laws are designed and purposed to manage and control and, hopefully, reduce pollution caused through anthropocentric means. It is generally recognised and accepted that environmental degradation continues to escalate through all environmental media, as evidenced, for example, through scientifically accepted climate change leading to natural disasters of increasing magnitude and frequency. At the same time the number and complexity of environmental laws being introduced in an effort to counter this, continues to rise, leading in turn to an exponential rise in environmental litigation.

The current reality is therefore that there is an escalation in environmental pollution and degradation, while at the same time there is an increase in environmental litigation, and therein lies the apparent paradox. One would assume that the two would be inversely proportional: increasing environmental laws and litigation leading to a reduction in environmental pollution and degradation, and yet both continue to rise.

Albert Einstein's statement that "*insanity is doing the same thing over and over and expecting different results*", seems applicable here. Are we achieving anything, or at best are we achieving pollution reduction quickly enough, by simply increasing, year on year, the number of environmental cases we take to court? That is not to say that we can or should replace the option of using courts to resolve environmental disputes. There will always be situations that cannot be resolved through other means, or where a judicial pronouncement on a particular issue or legal principle is desirable, for example in order to establish a precedent. However, if we want to achieve real and faster reductions in the impacts caused by pollution, it may be time to look at alternative solutions that are more constructive in an effort to break the cycle so that dispute resolution improves the environment. Time may be our greatest enemy; we are simply running out of it to reduce adverse environmental impacts. Now, perhaps more than ever before, we need to look for alternative ways to find each other in terms of understanding seemingly irreconcilable differences, and identifying compromises that are realistic and achievable and which will provide momentum to improving the environment and reversing the harm we have done.

Is environmental law an ass?

South Africa is a modern constitutional democracy, and one of only a few countries which has an entrenched constitutional environmental right from which a plethora of contemporary environmental legislation has evolved since 1996. From the overarching National Environmental Management Act, to the numerous media and sector specific laws and standards regulating air, water, waste, biodiversity, the marine environment and protected areas. This is in turn supported by a web of enforcement officials in all three spheres of government. So, it seems, at least at first glance, unfair, and perhaps unrealistic, to suggest as Charles Dickens' character Mr Bumble did in *Oliver Twist*, that our body of environmental law is an ass in terms of its application.

Yet the increase in the prosecution of pollution offenders for "low hanging fruit" offences such as air emission exceedances, (often using the offenders' own data to convict them), suggests an over rigid application of the letter of the law which may be contrary to common sense.

We aren't talking about offenders who deliberately dump chemical waste onto an open field, for example, or who negligently leave a valve open so that harmful effluent pours into a river, or who fail to conduct repairs to broken effluent infrastructure so that raw sewage enters the environment for months. These offenders should face the full might of the criminal justice system both to punish and to set a clear example to others. But to drag offenders to court because they exceed an emission limit set in a licence a couple of times a year, is lazy, counter-productive and leads to grudge compliance by the "offender". These "crimes" are often not prosecuted in other jurisdictions. They don't go unpunished, but rather administrative fines are levied as opposed to criminal prosecutions. Even then, in a country desperate for economic upliftment, an attempt at least by the authorities to sit down with the offender and establish if there is a means through which improvements can be made to reduce emissions exceedances, may be more constructive and desirable. The legislative "stick" is always still there is that fails.

Similarly holding on rigidly, (and unreasonably), to a conservative definition of "waste" by officials when their own National Environmental Management: Waste Act and National Waste Management Strategy, dictates otherwise – that to reduce waste streams and waste disposal, raw materials should be used to their full extent and be classified as waste as a last resort – again suggests an overly rigid and destructive application of our law.

The body of South African environmental law is clearly not an ass, but its application can be.

Environmental justice

Communities and environmental activists in South Africa enjoy, and are increasingly using, their right to challenge government or private decisions or actions which they believe harm the environment and impinge on their use and enjoyment of it. Over the last ten or fifteen years there have been a number of important cases taken before our courts by private parties to protect their rights and interests, several of which have set important precedents, but several of which haven't.

These cases generally have a common theme of mistrust and distrust between the parties with each believing the other has a hidden agenda. It's a winner takes all situation with the loser often left with expensive legal costs and a court order which they grudgingly and sparingly comply with, or where they feel let down by the judicial system.

The limitations of environmental litigation

There will always be a place for litigating environmental disputes, but the process comes with its limitations. Litigation is expensive, slow and positional rather than conciliatory. Environmental disputes can be scientifically complex and generally lawyers running the cases are not scientists, nor are the judges hearing them. The ability of the court to understand the case and arrive at the correct decision may therefore be a challenge.

By the time a decision is handed down, the environmental harm may have already occurred, or the where the challenged project or process is vindicated, the cost may have escalated, or the opportunity passed and with it the socio-economic benefit, or the reputational harm may have been done. In most instances, at least when it comes to climate change, the effect would in any event have continued all the while the matter was being adjudicated by our courts.

If the goal is to reverse or prevent environmental harm, then we are running out of time – time which we cannot, in many instances, afford to waste litigating for years.

We need to find each other

Environmental issues are emotive, especially where the impacts are becoming increasingly visible. This on its own can make it difficult for a party to a dispute to contemplate a compromise. Yet, if the parties were prepared to view the dispute in a different light; if they were prepared to shift from a positional engagement to an interest based one, the possibility for compromise becomes more realistic. Instead of adopting standpoints at the opposite end of the spectrum of environment only or profit only, can the parties consider each other's interests and can they contemplate balancing them? Instead of bargaining or haggling to get their way, can they consider problem solving for their mutual benefit by looking for options and agreeing to solutions?

Sometimes achieving a measure of improvement in the environment is better than no improvement at all, and can start a process that leads to more extensive gains. Solving a problem by tackling it one bite at a time, may lead to a longer term, more permanent and more sustainable outcome. It may be more constructive for parties in a dispute to collaborate to achieve a desired outcome, rather than one forcing the other to capitulate. Instead of the environment only at all costs and no development, or profit only with minimalist compliance, what about finding a way for the environment and business to coexist? What if allowing a mining project to go ahead thus generating much needed investment and social upliftment, but in a way that not only keeps it out of the most sensitive areas, but also commits the mine to restoring and reconnecting the mined areas to the protected environment, leads to a net environmental gain in the long term?

Fora exist to explore these possibilities in environmental disputes.

Mediation in our law

There are at least three statutory mechanisms available to mediate environmental disputes.

Firstly Chapter 4 of the National Environmental Management Act 107 of 1998 provides an opportunity for disputes to be referred to conciliation or mediation to see whether they can be resolved. It permits an authority to direct, a court to order or a private party to request referral to conciliation. Where this occurs, the conciliator must endeavour to resolve the dispute by obtaining and considering all relevant information, mediating the differences or disagreements and making recommendations to the parties. Despite being available since 1998, it has not been widely used.

The second is section 150 of the National Water Act 36 of 1998 which the Minister may at any time and in respect of any dispute between persons relating to any matter in the Act, and at the request of a person involved or on the Minister's own initiative, direct that an attempt to settle the dispute through a process of mediation and negotiation, be made. Again, this is an avenue which has been available for over twenty years, but has not been well used.

Lastly and most recently, Rule 14A of the High Court Rules requires a plaintiff or applicant to file with their founding papers a notice indicating whether they agree to or oppose referral of the dispute to mediation. A defendant or respondent must in turn file a notice indicating whether they agree to or oppose mediation. The parties to the litigation can agree to mediate the dispute at any point prior to judgment in the matter being handed down.

The benefits? Apart from being voluntary and without prejudice, mediation is much quicker and cheaper; it's also more flexible and informal. The mediator, who must be independent and impartial, can also be selected by the parties to ensure that he or she is a subject expert and thus equipped to understand the technical nature of environmental disputes. Importantly the parties themselves determine the outcome of the process, making it constructive. Its human nature to be more committed to a solution that you have identified and bought into, than to one which was imposed upon you.

While not a panacea for solving all disputes, we stand on the precipice of so many failing environmental indicators that we need to try something different to slow the rate and reverse the harm. Finding a solution together may be one answer; it may be the only answer.

Editorial

A call for action: Air Pollution, a serious health and economic hazard suffocating Africa

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Air pollution research has been conducted in Europe and North America as well as in Asia and South America for decades, but there has, so far, only been a limited amount of studies on air pollution and its health effects conducted in Africa. Until recently, global inventories of pollutants from North America Europe and Asia have been used for air quality and climate change modelling in Africa (Bond et al., 2004, Streets et al., 2004, Bond et al., 2007, Klimont et al., 2009, Klimont et al., 2013, Lamarque et al., 2010). Research in air pollution has, however, been lagging far behind in African countries, despite the increasing health- and economic impact associated with air pollution in these nations, since systematic monitoring in Africa is often lacking. The health impact of air pollution in African cities has only been sparsely studied: a review from 2018 (Coker and Kizito, 2018) found only 3 studies outside South Africa. Earlier last year, a study showed that air pollution was responsible for 1.1 million deaths across Africa in 2019, with household air pollution—driven largely by solid biofuel used in indoor cook stoves—accounting for 697 000 fatalities (64% of the total), while increased outdoor air pollution claimed 394 000 lives (36% of the total) (Fisher et al., 2021).

Although 60% of the African population currently lives in rural areas, urbanization is ongoing across the continent at a speed unprecedented in history. Projections show that Africa have the fastest urban growth rate in the world: Africa's cities will, by 2050, be home to an additional 950 million people (OECD/SWAC, 2020), and the continent's population is anticipated to be primarily urban by 2035. Several studies summarized in November 2021 by the Washington Post, project that by the end of this century, thirteen of the world’s 20 biggest urban areas will be in Africa — as compared to just two today. The population is growing faster than the supporting infrastructure, leading to changes in urban environments that are hard to control. The World Health Organization (WHO) estimates that the annual median concentration of air borne particulate matter smaller than 2.5 µm ($PM_{2.5}$) surpassed 26 µg/m^3 across more than half of the African continent, greatly exceeding the WHO limit of 5 µg/m^3. In a review of eight studies of outdoor air pollution in African cities (covering seven countries), $PM_{2.5}$ levels varied between 40 and 260 µg/m^3 (Naidja et al., 2017), compared with an annual average of 13 µg/m^3 in urban Europe (EEA, 2019) and 9 µg/m^3 in urban United States (IQAir, 2020) in 2019. Air pollution monitoring in Africa is severely lacking; among the 47 countries comprising sub-Saharan Africa, only 6 provide long-term data on PM, covering a total of 16 cities. The few available emission inventories are seldom precise and are typically based on indirect data, such as surveys, for example of fuel consumption. The scarcity and lack of data can significantly limit the planning and implementation of mitigation strategies. While new advances in remote and low-cost ground sensor technology and communication can serve as important tools for developing mitigation strategies and policy, the data quality and lack of proper calibration may become a barrier to these approaches.

African PM emissions originate from sources different from those in high-income countries. In Africa, biomass burning (including agricultural burning and wild fires) is one of the major sources of aerosols after Saharan dust (Dajuma et al, 2021). Globally, biomass burning make up a majority of primary combustion aerosol emissions with ~52% originating from Africa, (Bond et al., 2013, Andreae, 2019, Brown et.al, 2021). Africa accounts for about 72% of the total global burned area and about 52% of the total carbon emissions from biomass burning, including 44% of CO emissions, 36% of CH4 emissions (van der Werf et al., 2010), and 60% of the total black carbon (BC) emissions, which is twice the global average (Bond et al, 2013). Recent estimates show that Africa’s fires emission estimates are 31-101% higher than previous estimates (Ruben et al, 2021).

The predominant contributors to outdoor air pollution in urban areas are likely the extensive number of old unregulated motor vehicles, households burning biomass fuels, and domestic waste burning. The vehicle fleet is most probably the greatest contributor to outdoor urban air pollution (Hitchcock et al., 2014). The exhaust from road transport is of great concern because (1) the vehicle fleet is old and poorly maintained and do not meet emission standards of developed nations, and are imported without air filters and catalytic converters, (2) a significant increase in two-wheel two stoke engines that use gasoline and dirty oil, (3) considerable increase in the number of vehicles without adequate city planning leading to congestions and engines running idle, and (4) lack of emission standards and regulations in almost all African cities.

While wild fires are a major source of emissions in the continent contributing to ambient air quality, indoor air quality is also heavily influenced by biomass burning. Some surveys indicate that 95% of the population use solid biomass for cooking, due to lack of access to clean energy, and the International Energy Agency have projected that over 600 million people in Sub-Saharan Africa will still remain without access to electricity in 2030 (IEA, 2017). Domestic biomass burning contributes to high indoor as well as outdoor air pollution levels. Indoor air pollution is the largest environmental health risk factor in Africa. Domestic use of biomass burning causes nearly 600 000 premature deaths in Africa annually (WHO, 2014). An additional 43 000 premature deaths in Africa are linked to biomass burning driven by agriculture (Bauer et al., 2019).

According to recent health impact assessments, sub-Saharan Africa suffers the highest burden of disease and premature deaths attributable to environmental pollution in the world. These studies, however, rely on effect estimates from other parts of the world when it comes to ambient air pollution. This could lead to an underestimation of the impacts as the continent has lower access to healthcare, prevalence of infectious diseases, and differing sources of air pollutants. More than 80% of African children live in households where unclean sources of energy are used and, consequently, air pollution is a serious threat to child health (Masekela and Vanker, 2020). A study attributed one in five infant deaths in Africa to air pollution (Heft-Neal et al., 2018). The number of deaths attributable to air pollution globally is projected to double by 2050 (Lelieveld et al., 2015) with many of these deaths predicted to occur on the African continent.

The increasing air pollution will have economic consequences not only in health care costs, due to the increasing morbidity and mortality, but also in diminished economic productivity and human capital formation, and thus undercutting development. Recent numbers have shown that the overall loss in economic output due to air pollution mortality and morbidity in 2019 was USD 3.02 billion in Ethiopia, 1.63 billion in Ghana, and 349 million in Rwanda (Fisher et al., 2021). Even though air quality is a serious issue affecting health, mortality, and productivity it does not get enough attention due to other pressing social, political, economic, and health-related problems, creating a negative feedback loop.

A recent review by Abera et al., (2021) highlights the importance of focusing on air quality in the process of sustainable urban development in Africa. The topic is timely as the African continent is now undergoing rapid urbanization with an extreme shortage of air pollution data. Immediate action is needed to address the issue of air quality, because:

- Air quality emissions in Africa affect atmospheric composition globally much as we have seen from the rapid development of economies in East and South Asia in recent decades. Africa is one of the fastest growing regions of the world and understanding its emissions in this decade will provide a baseline against which anticipated large and rapid changes may can be assessed. There is an urgent need to conduct extensive air quality monitoring and extensive field campaigns to conduct measurements and understand the chemistry and nature of pollutants in African megacities to provide mitigation strategies to policy makers. An example of such an initiative is the MAIA investigation (https://maia.jpl.nasa.gov) that will provide real time chemically speciated air pollution data from two primary target areas (Addis Ababa and Johannesburg) and six secondary target areas (Dakar, Accra, Lagos, Cape Town, Nairobi, and Harar) in Africa.

- While air pollution in India, China, and other emerging economies has become a major area of concern for scientists and policy makers, in those countries and worldwide, the issue has gained little traction in Africa where it is taking a serious toll on human health and on the economy. Air pollution kills more Africans than other major risk factors. Experience has shown that efforts to mitigate air pollution results in positive impacts on health, human well-being, the economy of the affected countries. Economic growth and viability are linked to clean air and the health benefits of clean air. The long-term economic and health benefits of clean air need to be clearly explained to policy makers so they can make short-term painful decisions to limit pollution.

- Another challenge is that the scientific capacity in Africa, though growing, is far more limited than in the more heavily sampled regions of North America, Europe, and Asia. Several research groups and agencies in Europe and the US are developing air quality monitoring capacity in several African megacities. However, the effort is likely insufficient to keep pace with the rapid growth of these urban areas and the increase in pollution. Even with the ongoing efforts there are challenges with data sharing of measurements currently conducted in Africa. An initiative to increase number of African scientists in the field and to consolidate existing data and provide easy access to this data, in order to build capacity and knowledge together, is likely as important as adding new measurements.

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MINE DUST NETWORK

The Mine Dust and Health Network was established in July 2019, through a research grant from the Global Challenges in Research Fund (GCRF), as part of the United Kingdom Research and Innovation

The network serves as a collaborative think tank and brings together stakeholders from different disciplines and interest groups. The interdisciplinary and collaborative approach which embraces a wide range of perspectives, seeks to shape research and inform policy in the complex and poorly understood space of mine dust and its impacts on the health of communities.

Our desired outcomes

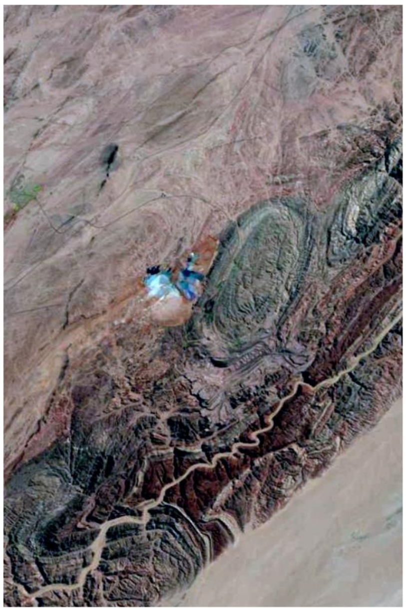
Integrated solutions to mine dust tailored to resource limited environments and **co-created** by academics and all other relevant stakeholders

Government **policy** and **regulations** for managing mine dust health impacts are **meaningful** and **effective**

Capacity sharing and **knowledge exchange** enabling wide dissemination and application of research **results**, and increased potential for **future funding**

Thought leaders of the future to **influence** the social, regulatory and professional environments of their **resident countries**

Communities are better **informed** and **empowered** to take **ownership** of their own **well-being** and **future**



- The network provides a platform for conversations to share information and to collectively develop solutions for a healthy environment and healthy communities.
- Membership and participation in the network are entirely voluntary and is underpinned by a shared commitment to the well-being of affected communities.

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News

Scientists discuss the state of air quality research in Africa during the First International Conference on Air Quality in Africa – ICAQ'AFRICA2022

Bertrand Tchanche[1], Khanneh Wadinga Fomba[2], Wahid Mellouki[3], Daniel M. Westervelt[4] and Michael R. Giordano[5]

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ASAQ

INTERNATIONAL CONFERENCE ON AIR QUALITY IN AFRICA (ICAQ'Africa 2022)

11-14 October, 2022 (VIRTUAL EVENT)

The African Society for Air Quality (ASAQ) was constituted on the 1st of June 2021 to bring together all specialists and researchers whose work aims to improve air quality in Africa. This year the ASAQ organized its first annual conference, which took place on 11-14 October 2022 in a virtual format.

The conference program included technical sessions, keynote talks, special sessions, and roundtable discussions. A total of 66 talks were presented in different sessions organized around several topics. Half of the talks were on pollutants covering topics such as, sources, characterization, monitoring, and forecasting models. Plenary talks were given on diversified topics which included, particulate matter from biomass fuels, microplastics, the impact of atmospheric pollution on climate, remote sensing, air pollution and health effects, the impact of air pollution on development, the urban heat island and mitigation strategies, in-kitchen and in-car aerosol exposure in global cities, and air quality community of practice.

Four roundtable discussions were made to interact with the audience: (1) Air Pollution in Africa: Pollutants, Sources and Data, (2) How Does Air Pollution Affect Africans?, (3) How do Governments Protect Clean Air in Africa? and (4) How to Provide Training and Strengthen Research and Collaboration in the Field of Air Quality. Special sessions, three in total were organised to allow our sponsors (IQAir, CAMS-Net, Clarity Movement, Health Effects Institute) to introduce their respective organizations to the audience.

Table 1: *Breakdown on the different contributions in the various topics within the program*

Technical sessions	Number
Sources and characterization of air pollutants	11
Ambient and indoor air quality measurements	9
Materials for sensing devices	2
Data, Modelling and forecasting	7
Air pollution and health effects	5
Policy, regulation and public awareness	6
Research, collaboration and innovation	4
Poster	6
Plenary	13

There were 160 participants from 47 countries registered with the highest number of online participants recorded at around 85 on the first day. The USA had the highest number of registrants (26) followed by Nigeria (19).

Through this conference, ASAQ achieved an important goal, bringing together researchers to discuss air pollution in Africa. At the end of the conference a number of conclusions can be drawn. There is a lot of ongoing work in Africa with contributions received at the conference from the following countries Ghana, South Africa, Kenya, Malawi, Angola, Senegal, Togo, Ethiopia,

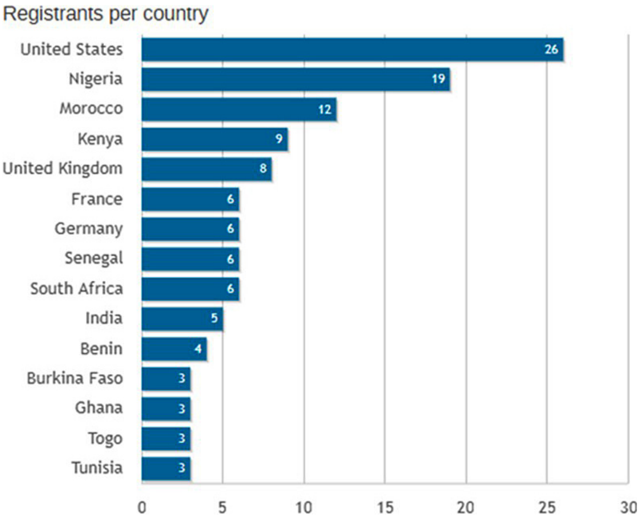

Figure 1: *Distribution of registrants by country totalling 160 registrants from 47 countries*

Rwanda, Cameroon, Nigeria, Morocco, Algeria, Tunisia, Cabo Verde. Most of the presentations showed that air quality is poor in most major African cities. However, there are still some places where no data are published or were presented like Somalia, South Sudan, Guinea, and Mauritania. The lack of data is due to several factors, including, the high upfront cost of monitors and their poor maintenance where they exist, low awareness among decision makers and the general public, and lack of well-trained personnel. A good number of studies were presented around low-cost sensors which are being considered as a potential solution to overcome the lack of data in Africa. IQAir offered the possibility of collaboration with ASAQ to increase the number of monitoring stations in Africa. A few presentations were on air quality data retrievals via remote sensing using satellites. This was a discovery for most participants, who didn't have experience with satellite data.

The third day of the conference was dedicated to air pollution and associated health risks. Atmospheric pollutants, such as particulate matter (PM), and gaseous pollutants (nitrogen oxides, ozone, sulphur dioxide, volatile organic compounds, etc.) are responsible for a number of diseases (asthma, cancer, stroke, dementia, etc.) leading to morbidity and premature mortality. Five recognized leaders in this topic gave very informative talks: Prof. Philip Landrigan (Boston College - USA and Centre Scientifique de Monaco – MC), Dr. Pallavi Pant (Health Effects Institute, USA), Dr. Patrick Katoto (Catholic University of Bukavu (DR Congo) and University of Cape Town (South Africa)), Prof. Christina Isaxon (Lund University, Sweden), Prof. Kevin Cromar (New York University, USA), Prof. John Balmes (University of California, San Francisco (UCSF), USA), and Dr. Nonvignon Marius Kèdotè (University of Abomey-Calavi, Benin).

The last day saw a wealth of talks on policy, public awareness, and legislation. Weak government actions on air pollution mitigation were highlighted. In most places, legislation related to air pollution exists but is not enforced. Unfortunately, the participation of policy and law makers was limited, reducing the impact of discussion on low public awareness, weaknesses in the creation of new policy, and the obstacles to the implementation of existing legislation. Prof. Matheos Santamouris, from the University of New South Wales (Australia) during his talk emphasized on the need for African researchers to study the urban heat island effects in African cities and adopt newly developed cool roofs. He also stressed the negative impact of heat islands on productivity and the economy in most African cities, inviting governments to take action.

Figure 2: *Installation of low-cost monitors in the campus of the University of Douala, Cameroon (credit: LCS-WACA project)*

The conference was also an occasion for networking, and discussion took place around training, research, and collaboration. Most participants pointed out the lack of south-south collaboration and the need to organize trainings in the field of air quality. Proposals were formulated to strengthen collaboration with the North, foster collaboration with the African diaspora, and organize more workshops for capacity building.

The conference was attended mostly by students and researchers who heard about ASAQ activities for the first time. The number of ASAQ members by the end of the event doubled. The majority of the audience recommended a follow-up event but in the in-person meeting format. The committee announced the next conference is planned in Morocco, in 2023.

The ASAQ is open to all researchers and specialists working in the field of air quality and those interested in joining us can send their application at afs4aq@gmail.com.

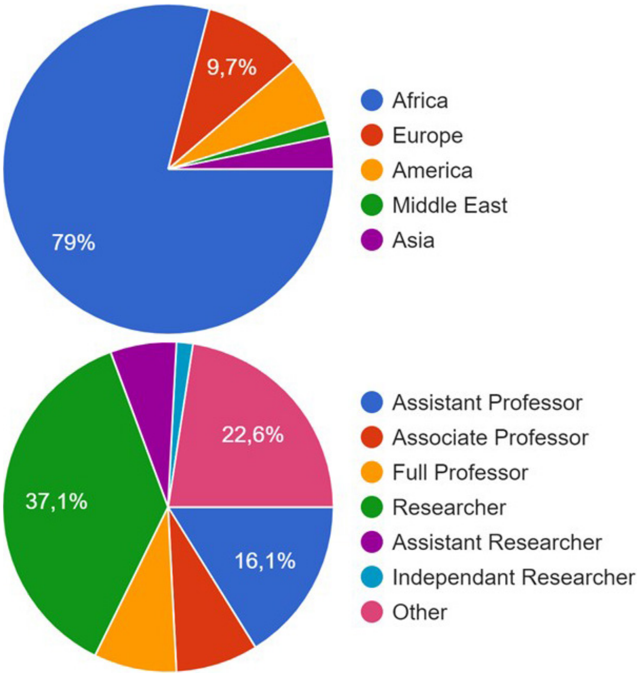

Figure 3: *Distribution of ASAQ members (61) by region and by job title, of which 79% are within Africa*

The conference gave awards to the following:

Best presentation award

Impact of urban emissions on regional air quality in Fez city area, Morocco

Deabji Nabil[1,2], Fomba Khanneh Wadinga[1], Poulain Laurent[1], dos Santos Souza Eduardo José[1], Mellouki Abdelwahid[3], and Herrmann Hartmut[1]

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[2]Faculty of Science, Mohammed V University in Rabat, 4 Avenue Ibn Battouta, B.P. 1040, 10100 Rabat, Morocco

[3]Institut de Combustion Aérothermique Réactivité et Environnement, OSUC-CNRS, 1C Avenue de la Recherche Scientifique, 45071 Orléans CEDEX 2, France

Best poster award

Relationship between meteorological parameters and $PM_{2.5}$ in Accra

Victoria Owusu-Tawiah[1], Daniel M. Westervelt[2] and Thompson Annor[1]

[1]Kwame Nkrumah University of Science and Technology, Department of Physics, Kumasi, Ashanti Region, Ghana

[2]Columbia University, Lamont-Doherty Earth Observatory, 61 Route 9W, Palisades, NY 10964

Acknowledgements

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- ✓ Air Quality Training & Development
- ✓ Climate Risk & Assessment

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Sustainable Development Goals

News

The launch of the first-ever Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa

Alice Kaudia[1], Youba Sokona[2], Brian Mantlana[3], Aderiana Mbandi[4,5], Philip Osano[6], Anderson Gwanyebit Kehbila[6], Lawrence Nzuve[6], Caroline Tagwireyi[7], Charles Heaps[8], Kevin Hicks[9], Eve Palmer[9], Bianca Wernecke[10,11] and Rebecca M Garland[12]

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[7]Ampelos International Consultancy, Harare, Zimbabwe
[8]Stockholm Environment Institute (SEI), Seattle, WA, USA
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[10]Environment and Health Research Unit, South African Medical Research Council, Johannesburg, South Africa
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November 2022 saw the release of the "Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa - the Summary for Decision Makers Report" (UNEP, 2022), by the African Union Commission (AUC), the Climate and Clean Air Coalition (CCAC), and the UN Environment Programme (UNEP) at Climate COP27 (Figure 1). Developed by African scientists and supported by the Stockholm Environment Institute (SEI), the report unpacks how short-lived climate pollutants (SLCPs), greenhouse gases and other polluting emissions play a role in sustainable development in Africa. It also considers strategies, policies, and measures to mitigate these pollutants, while supporting development and human health and wellbeing in Africa on a warming planet. This is the first time that such detailed and harmonized Pan-African assessment on air quality and climate change has happened. Not only will the results of the Assessment provide a critical evidence base for decision-makers across the continent, but the underlying emissions data and tools will be open access to support further studies, and policy measures. In 2022 at the Eighteenth Ordinary Session of the African Ministerial Conference on the Environment (AMCEN-18), African Ministers stated their support of the Assessment and of measures to mitigate SLCPs and ''urge African countries to support further development and implementation of the 37 recommended measures as a continent-wide Africa Clean Air Program, coordinated by strong country-led initiatives, cascaded to the Regional Economic Communities and higher levels of policy" (UNEP and AMCEN, 2022).

Using harmonized emission inventories and projections, climate chemistry model (GISS-E2.1-G model; Kelley et al., 2020) simulations were driven to estimate the impact of these emission on climate and air quality on the African continent. These future projections of climate and air pollution under the three scenarios were then used to quantify the impacts of a changing climate and of air pollution on societal issues, such as food production and human health.

Figure 1: *The Assessment Summary for Decision Makers Report launched at Climate COP 27 in November 2022 (photo courtesy of Lawrence Nzuve, SEI Comms officer at SEI Africa).*

Ultimately, the report puts forward 37 recommended measures which have the potential to greatly reduce emissions causing air pollution and climate change, as energy consumption increases in Africa to meet socio-economic development objectives. The 37 recommendations span across the five key areas of 1) Transport 2) Residential energy 3) Energy generation and Industry 4) Agriculture and 5) Waste management (Table 1). If the emission reductions are achieved from these measures, it is estimated to prevent 180 000 premature deaths attributable to ambient air pollution per year by 2030 and 800 000 premature deaths attributable to ambient air pollution per year by 2063. Indoor air pollution would also be substantially improved. Gains in crop yield across Africa would result from decreased warming, changes in precipitation and reduced ambient ozone concentrations. For more on the Integrated Assessment of Air Pollution and Climate

Table 1: *. Overview of the five areas and 37 measures modelled by the Africa Assessment*

Transport	Residential	Energy	Agriculture	Waste
1. Cleaner existing transport	9. Clean lighting	14. Efficient charcoal making	25. Efficiency of livestock production	32. Landfill to reduce waste burning and capture methane
2. Better and more public transport Options	10. Clean cooking	15. Emission control in industry	26. Improved livestock feed to reduce emissions	33. Methane capture at wastewater plants
3. More electric vehicles	11. Efficient air conditioning	16. Coal mining methane capture	27. Improved manure management	34. Waste collection and new sanitary landfills
4. More hybrid vehicles	12. Efficient refrigeration	17. Oil and gas methane loss reduction	28. Alternate wet and drying for rice production	35. Organic waste to compost and biogas generation
5. More cycling and walking	13. Household energy efficiency	18. Implementing the Kigali amendment	29. Eliminate burning of crop residues	36. Reduce organic waste
6. Freight from road to rail		19. Reduce electricity transmission and distribution losses	30. Reduce food waste	37. Improved water and sanitation services
7. Rail electrification		20. Industrial energy efficiency	31. Healthier diets	
8. Road freight electrification		21. Service sector energy efficiency		
		22. Cement making energy efficiency		
		23. Carbon capture and storage		
		24. Shift to renewable energy		

Change for Sustainable Development in Africa and for more details about the 37 measures go to: https://wedocs.unep.org/handle/20.500.11822/41223;jsessionid=D6416F58EE121485F5A03D2E5E2610AF

Practical guide on data availability and tips for access

The emissions modelling output for the Assessment was at the national scale. SEI is making the underlying modelling freely accessible via an open-source distribution model. The modelling has been developed within SEI's LEAP energy modelling software, and people wishing to view the model will need to have LEAP installed on a Windows computer. The model will be freely available for download from the LEAP website and will also be accessible from within LEAP itself. The Africa-wide model is quite large, as it contains detailed data and results for all African countries. Thus, it requires the use of a fairly powerful computer. A modern PC with a fast CPU and at least 8 GB of RAM are recommended as a minimum specification.

The Africa-wide model will also be "sliced-up" to create individual national-scale models, which will be useful to countries as they work to develop their own climate and air pollution plans. These national-scale models will be distributed in the same fashion as the main African model.

The evaluation version of LEAP is freely available to download and install and can be used without a license to view all the data and results in the Africa assessment model (https://leap.sei.org). If users wish to further develop the Africa model (i.e. make changes to it) they will need to obtain a license for LEAP from SEI. These licenses are available at no cost to governments, NGOS, and academic organizations in low-income and lower-middle-income countries, and to students worldwide. Special low-cost licenses are also available to these types of users in upper-middle-income countries. All other users will need to purchase a standard license from SEI.

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GAS ANALYSIS

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Research Projects

Environmental and ambient air gases
Development of the following reference gas mixtures:

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  - Carbon dioxide, methane, Sulphur hexafluoride, nitrous oxide
- **Low amount fraction reactive gases**
  - Nitrogen monoxide, nitrogen dioxide, hydrogen sulphide
  - Preparation of calibration gas mixtures using dynamic volumetric methods
- **Volatile organic compounds**
  - Non-methane hydrocarbons (NMHCs), Hazardous Air Pollutants (HAPs), oxygenated VOCs, benzene, toluene, ethyl benzene, (o,m,p) xylenes
- **Sulphur compounds**
  - Sulphur dioxide, Ethyl mercaptans, Dimethyl sulphide, Tetrahydrothiophene

Industrial emission and energy gases
Development of the following reference gas mixtures:

- **Stack emission gases**
  - Nitrogen monoxide, sulphur dioxide, carbon dioxide
- **Automotive exhaust gases**
  - Carbon monoxide, carbon dioxide, propane, oxygen
- **Natural gases**
  - Ethane, propane, n-butane, n-pentane, i-pentane
- **Refinery gases**
  - Carbon dioxide, carbon monoxide, methane, ethane, propane, 1,3-butadiene, oxygen nitrogen and helium (balance)
- **Development of the Biogas gas mixture**
  - Methane, carbon dioxide and hydrogen sulphide

Research brief

Summary of research article published in Energy for Sustainable Development titled: The effectiveness of household energy transition interventions in a coal-using community on the South African Highveld

Bopaki Phogole[1], Clare Kelso[1], Kristy E. Langerman[1]

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Globally, it is estimated that 2.6 billion people rely on dirty fuels such as coal and biomass to meet their household energy needs (IEA et al., 2021). The use of such energy sources has negative impacts on human health and the environment with an estimated 4.3 million annual deaths attributed to dirty energy sources (Landrigan et al., 2018). Factors such as poverty and unemployment, lack of clean energy infrastructure, and affordability barriers are some of the leading drivers of the persistent use of dirty fuels in South Africa. Against this backdrop, there is an urgent need to facilitate the use of cleaner energy sources, especially in low-income communities. The need to transition away from burning dirty fuels and achieve universal access to clean energy is a shared global target that forms part of the United Nations' Sustainable Development Goals (2030). However, the road to achieving this goal is unclear. The progress towards eradicating dirty fuels, especially in low-income areas, is hampered by region-specific socio-economic challenges together with individual preferences. Additionally, targeted clean energy intervention programmes need to be sensitive and responsive to factors that may hinder the continued use of clean energy.

In our recent study, Phogole et al. (2022), we assess the effectiveness of a clean household energy intervention designed to facilitate the use of cleaner energy sources in a coal-using, low-income community 3 to 5 years after the interventions were implemented. The study follows an Eskom-led pilot project in KwaZamokuhle on the Mpumalanga Highveld that provided households with clean energy alternatives which included low-emission coal stoves, liquid petroleum gas (LPG) heaters and stoves, and electric heaters and stoves. The houses of participating households were also fitted with thermal insulation to reduce the demand for energy for heating, especially during winter seasons when energy consumption peaks. In our study, we targeted 53 households that participated in the Eskom project (and 51 non-participant households as a control group), and a set of questionnaire surveys and visual observations were used to collect data on the households' energy use patterns, energy expenditures, and the current state and use of the provided energy interventions. The households' satisfaction with the provided interventions was assessed using criteria that interrogated the interventions' perceived safety, durability, ability to reduce indoor air pollution, reduce energy-related expenditure, and maintain indoor cleanliness and aesthetics.

All the provided electric stoves (100%) and most of the improved coal stoves (84.6%), LPG stoves (78.6%), and LPG heaters (85.7%) were still used by the households. The electric heaters, in contrast, were used by only 46% of the households. The electric heaters fell out of favour due to their perceived poor heating capacity. Participant households also pointed to the rising costs of electricity coupled with the increasing frequency of electricity outages as some of the key factors that negatively affect the desirability of using electric appliances. Although most interventions were still operational, only 41.7% of the improved coal stoves had all their working parts in place, and this points to the poor durability of the stoves. The dual use of coal stoves for both cooking and heating may accelerate the deterioration of their structural integrity. Households that were provided with LPG appliances were largely concerned with the safety implications of using gas although all of them acknowledged the receipt of relevant user training and there were no reported gas-related incidents. Regardless of the reported limitations, households reported high levels of satisfaction with all the interventions with exceptionally high levels of satisfaction with the improved coal stoves and, most especially, electric stoves.

The installed thermal insulations were effective in reducing energy demand however, the implementation of this intervention needs to consider the quality of the house and its implication on the quality and aesthetics of the insulation (faulty roofing may cause water leakage that diminishes the quality and beauty of the insulation, especially the ceiling insulation). Additionally, the proliferation of informal housing structures may be linked to the persistent use of coal, and this needs to be addressed in pre-programme planning to ensure the sustained use of cleaner energy alternatives.

These findings need to be interpreted within the local context and acknowledging the important role of local social and economic characteristics. Nevertheless, the results of this study suggest that a successful transition away from coal requires that energy demand be reduced (for example, through insulation and energy efficient appliances), and that alternative energy carriers and appliances align with natural preferences for electricity and fuel stacking.

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Research brief

Tier 2 greenhouse gas emission factors for South African liquid and gaseous fuels

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The South African Greenhouse Gas reporting regulations (DEA 2017a) require that certain emission categories (including gaseous and liquid fuels for transport and stationary applications) use tier 2 methods to report greenhouse gas emissions starting five years after April 2017. Higher tier methods for greenhouse gas reporting require country-specific emission factors.

This brief reports on the results obtained from sampling and analysing petrol (ULP93 and ULP95), diesel, jet kerosene (also known as Jet A1), aviation gasoline, paraffin, and residual fuel oil (also known as heavy fuel oil). Country-specific emission factors were also determined for liquified petroleum gas (LPG), using appropriate empirical calculations representative of the South African market.

Samples of selected liquid fuels used in South Africa were collected over the summer and winter seasons of 2021 in the Gauteng, Mpumalanga, Free State, KwaZulu-Natal and Western Cape Provinces, primarily from large retail stations along major traffic routes (unleaded petrol ULP93 and ULP95 and diesel). Liquid fuels used in smaller volumes (bio-ethanol, paraffin, jet kerosene, aviation gasoline and heavy fuel oil) were also sampled at appropriate locations. Sampling of liquid fuels was conducted according to a standard operating procedure (SOP) developed for the project, based on EN 1475:2013 (CEN 2013).

All samples (343 in total) were analysed at the accredited SGS South Africa (Pty) Ltd Oil, Gas and Chemicals Division Laboratory in Durban. Determination of total carbon (TC) was performed using an SGS in-house method (NDIR-1) based on ASTM D5291 and ASTM D7662 (ASTM 2016, ASTM 2020). This method employs an elemental analyser based on nondispersive infrared (NDIR) spectroscopy. The calorific value of 199 fuel samples was also determined by method ASTM D4868 (ASTM 2010) to allow for the calculation of methane and nitrous oxide emission factors. Results were statistically analysed using method API 2572 (API 2013) to determine mean values and their uncertainties, identify outliers and determine correlations between variables. Results for ULP93 and ULP95 were weighted by their respective 2021 annual average sales volumes to obtain an average value for all types of petrol. Based on sales data from the years 2018-2021, summer and winter results were equally weighted to obtain annual average emission factors for ULP93, ULP95 and diesel, reflecting a slight decrease from the values contained in the Technical Guidelines for Monitoring, Reporting and Verification of Greenhouse Gas Emissions by Industry until recently being used by DFFE (DEA 2017b). A calculation-based liquefied petroleum gas emission factor, confirmed by analysis certificates from a few local suppliers, was found to be 3002 g CO_2/kg. For heavy fuel oil (HFO), the carbon content was found to be 85.93±1.58% and the density 0.994±0.12 g/l. The latter figure must be treated with some caution, as the fuel market conditions at the time of sampling required imports of HFO to be made, which is not normally the case.

Full results are given in tables 1 and 2 below. Detail of the methods used and of the correlation between variables studied are given in Kornelius et al (2022), while the Department of Forestry, Fisheries and the Environment has published the Methodological Guidelines for the Quantification of Greenhouse Gas Emissions providing information on the application of the results of the study (DFFE 2022).

Table 1: *National emission factors for carbon dioxide compared to the Technical Guideline values*

Fuel Type	National CO_2 Emissions Average (g/L), this study	Technical Guideline (DEA 2017b) (g/L)
Aviation gasoline	2229	2202
Jet kerosene	2528	2491
Diesel	2650	2692
Bioethanol	1470	Note 1
Residual fuel oil (HFO)	3124	2996
Paraffin	2424	2488
Petrol	2263	2302

Note 1: The Technical Guideline does not provide a value for bioethanol.

Table 2: *Carbon content, density and calorific value of liquid and gaseous fuels. 5% and 95% confidence intervals given*

	Fuel Type						
	Jet kerosene	Aviation gasoline	Diesel	Bioethanol	Paraffin	ULP93	ULP95
National Carbon Content Summer (g/L)	700.0±12		729.3±2.8			620.7±3.6	621.4±4.0
National Carbon Content Winter (g/L)	675.5±11	608.2±6.8	717.3±3.5	401.8±1.7	661.6±17	610.1±10	613.6±3.6

	Fuel Type						
	Jet kerosene	Aviation gasoline	Diesel	Bioethanol	Paraffin	ULP93	ULP95
National Carbon Content Summer (%)	87.97±0.99		88.31±0.79			84.13±1.3	83.60±0.47
National Carbon Content Winter (%)	85.42±1.0	85.08±0.84	87.00±0.38	49.88±0.25	86.48±0.67	82.66±0.44	82.68±0.33

	Fuel Type						
	Jet kerosene	Aviation gasoline	Diesel	Bioethanol	Paraffin	ULP93	ULP95
National Density Summer (kg/L)	0.797±0.006		0.826±0.002			0.738±0.002	0.743±0.002
National Density Winter (kg/L)	0.791±0.006	0.714±0.001	0.825±0.002	0.805±0.0001	0.765±0.02	0.739±0.003	0.742±0.002

	Fuel Type		
	Diesel	ULP93	ULP95
National CV (higher) Summer (MJ/kg)	45.93±0.09	46.94±0.23	46.97±0.10
National CV (lower) Summer (MJ/kg)	43.05±0.07	43.83±0.18	43.85±0.08

	Fuel Type		
	Diesel	ULP93	ULP95
National CV (higher) Winter (MJ/kg	45.85±0.043	47.08±0.085	47.00±0.028
National CV (lower) Winter (MJ/kg)	42.99±0.033	43.94±0.066	43.87±0.021

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Research article
Using student science to identify research priority areas for air pollution in a university environment: an Ethiopian case study

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Abstract
Students in a country like Ethiopia face a double air pollution challenge: they are frequently exposed (both outdoors and indoors) to sources of incomplete combustion and therefore to unhealthy concentrations of particulate matter ($PM_{2.5}$) and carbon monoxide (CO), while they also face increased carbon dioxide (CO_2) concentrations in crowded dormitories and classrooms. Research on air pollution in the environment of Ethiopian students is scarce. This lack of research can be fixed by involving students in science through a student science project, essentially a subset of citizen science. Students of Arba Minch University, Ethiopia, conducted measurements of $PM_{2.5}$, CO, and CO_2 under self-selected circumstances. Their measurements are compared to guideline values related to health effects to identify priority areas for future research. For $PM_{2.5}$, students' measurements show likely exceedances of guideline values for an inside coffee ceremony, close to open waste burning, at a bus station and close to a diesel generator. For CO, exceedances are revealed in kitchens and the visitor's area of restaurants using biomass fuel, close to outdoor charcoal cooking and close to waste burning. For CO_2, exceedances are found within student dormitories. These areas can be considered priority areas for further research. Students can conduct additional measurements to distinguish other relevant scenarios. Insight into exposure can be improved if, besides different concentrations under different circumstances, also time durations of these different circumstances are studied. The findings reveal that students themselves can be a partial solution to research and resource gaps in their context.

Keywords
Air pollution, $PM_{2.5}$, CO, CO_2, biomass burning, campus exposure, student measurements, citizen science, student science

Introduction
Air pollution poses one of the biggest current threats to health worldwide (Babatola, 2018; Gakidou et al., 2017; Shaddick et al., 2018). Ambient (outdoor) air pollution is estimated to cause 4.2 million premature deaths worldwide each year, especially due to exposure to particles with a diameter smaller than 2.5 µm ($PM_{2.5}$) (World Health Organization, 2018a; data for 2016). Another 3.8 million premature deaths can be attributed to indoor (household) air pollution (World Health Organization, 2018b). The burden of these premature deaths is especially carried by low- and middle-income countries, where air pollutant emissions are more prevalent due to the use of solid fuels like wood, charcoal, and dung as well as open kerosene fires (World Health Organization, 2018b). Besides particulate matter ($PM_{2.5}$), carbon monoxide (CO) is a common indicator of household air pollution (Leavey et al., 2015). Both $PM_{2.5}$ and CO are products from incomplete combustion, so higher exposure can be expected when people are close to combustion sources like traffic, waste burning or cooking practices.

While $PM_{2.5}$ and CO are useful measures of combustion-related air pollution, universities' indoor air quality measures often focus on carbon dioxide (CO_2). CO_2 is an indicator of quality of ventilation, and increased CO_2 concentrations have adverse health effects and on cognitive performance by causing drowsiness, headache, and loss of attention (Soomro et al., 2019). Such effects are a problem at campuses, where both a great deal of brainwork is needed, and a lot of people might gather in less-ventilated spaces.

Research on air quality and air pollution disproportionally favours some settings and scenarios over others. For instance, while outdoors air pollution is justifiably a focus of much research worldwide, work that considers it in relation to schooling tends to be limited to higher income countries, and little is known about the impact of air pollution for students in lower income countries (Chen, 2018). Likewise, while ventilation research has been conducted in a range of European countries, the USA, UAE, and India (Soomro et al., 2019), and indoor and outdoor measurements of air quality exist for universities in Spain and China (Alves et al., 2020) such studies are again rare for lower income countries. And yet it is precisely in lower income countries, where the topic of air quality in relation to higher education is especially urgent. For instance, students in a country like Ethiopia must deal with a combination of these air quality challenges. They frequently encounter combustion sources such as open waste burning, cooking with biomass fuels, and traffic consisting of older vehicles. Also, they spend a lot of time in crowded dormitories and classrooms.

As the lack of research clearly is not because of a lack of relevance, it must be due to a lack of awareness and/or resources. One of the most promising ways to tackle both awareness and resources problems, is to crowd-source measurements using relatively low-tech methods that can be widely deployed. This falls under the umbrella of Citizen Science: science carried out at least in part by lay people or by a broader community than professional researchers (Kimura & Kinchy, 2016). For the topic of air quality in higher education specifically, a particularly promising approach is Student Science: to let students conduct science, as part of the students' curriculum (Dingemanse & Dingemanse-de Wit, 2022). This combines the benefits of crowdsourcing associated with Citizen Science with the additional educational value offered by participatory research (Zoellick et al., 2012). Especially for work that focuses on students' environments, an obvious advantage is that students have easy access to their own environment, while it at the same time raises their awareness on such issues.

Here we report first results of a participatory research approach to crowdsourcing measurements in an institution of higher education in Arba Minch, Ethiopia. Students of Arba Minch University have conducted measurements of $PM_{2.5}$, CO, and CO_2 in a variety of self-selected air quality circumstances in their environment. This case of Student Science has been subject to a study in which it is found that Student Science can serve both scientific and educational needs typical for a university in Ethiopia (Dingemanse & Dingemanse-de Wit, 2022). The current study focuses on that scientific side and makes two main contributions. First, in several cases the measurements represent the first of their kind for a range of locations and activities that are frequent in many societies worldwide. This includes open waste burning, charcoal cooking, and restaurant kitchens that use biomass fuels, all of which are indicated as priority areas for further research. Second, this study shows that the Student Science research approach can address structural inequalities in access to measurements of air pollution and can improve our understanding of how air quality contributes to health and cognitive performance in societies around the world.

Literature review

$PM_{2.5}$ health effects and guideline values

Particles suspended in the air with an aerodynamic diameter smaller than 2.5 micrometre ($PM_{2.5}$) are associated with a variety of adverse health effects upon exposure, such as cardiovascular and respiratory diseases (Lu et al., 2015), as well as diabetes, adverse birth outcomes, and others (Feng et al., 2016). The health effects of $PM_{2.5}$ are diverse because $PM_{2.5}$ can consist out of many different components, including ammoniated sulphate, crustal material, carbonaceous components, oxides, and trace metals (Snider et al., 2016).

Health effects have been witnessed for relatively low concentrations, both for short-term (24-hour) and long-term exposure. In 2005, the World Health Organization (WHO) established guideline values for $PM_{2.5}$ with respect to the long- and the short-term: an annual average concentration of 10 µg/m³ and a 24-hour average concentration of 25 µg/m³ (World Health Organization, 2006). The annual guideline value was based on earlier research, such as the American Cancer Society's (ACS) study and the Harvard Six-Cities data. These studies showed that health effects can be expected for annual mean concentrations (long-term) already in the range of 11-15 µg/m³. The 24-hour average was based on an average concentration pattern, in which a concentration of 25 µg/m³ can be expected in 1% of the time (99th-percentile) if the annual average concentration is 10 µg/m³. The rationale for a short-term guideline value was provided by studies that showed an increased mortality of 0.5% for every 10 µg/m³ PM_{10} short-term increment, combined with the assumption that health effects were especially related to the $PM_{2.5}$ portion of PM_{10} (World Health Organization, 2006).

Indeed, newer studies have only added evidence to these findings. Atkinson et al. (2014) found that a *short-term* 10 µg/m³ increment of $PM_{2.5}$ is associated with a 1.04% increase in mortality. Kloog et al. (2013) found even a higher value, 2.8%, while also reporting health effects for every *long-term* 10 µg/m³ increment. A threshold below which no damage to health is observed, is not identified (World Health Organization, 2018a). Guideline values for concentrations of $PM_{2.5}$, therefore, reflect an aim to achieve the lowest concentration of PM possible, instead of a level at which no health effects are expected. In 2021, the WHO has updated the guideline values for $PM_{2.5}$ to an annual average of 5 µg/m³ and a 24-hour average concentration of 15 µg/m³, based on a review of newest studies (World Health Organization, 2021).

CO health effects and guideline values

Compared to $PM_{2.5}$, the adverse health effects of CO are relatively straightforward. CO binds with haemoglobin (creating COHb), thereby taking the place of oxygen. This results in a reduced transport of oxygen in the body. Health effects of CO are primarily short-term: during exposure to high CO concentrations, there is imminent threat. Unlike $PM_{2.5}$, there is a threshold below which no health effects are expected. Guideline values are based on a maximum level of COHb of 2.5% and known variables of CO uptake (World Health Organization, 2000). Based on this, for 15-minute, 30-minute, 1-hour and 8-hour periods the following guideline values are established: 100, 60, 30, 10 mg/m^3. This corresponds to 87, 52, 26 and 9 ppm (Boguski, 2006).

CO and PM

Both for $PM_{2.5}$ and CO, the main source for harmful concentration levels is incomplete combustion. For this reason, it has been hypothesized that one can be used as a proxy for the other (Northcross et al., 2010), removing the need of studying both. However, there are mixed results in this regard. Amongst other things, the ratio of CO to PM varies over the burn cycle and varies as a function of combustion source (Northcross et al., 2010). Leavey et al. (2015) found that $PM_{2.5}$ and CO correlated differently to different fuel-related variables.

Besides a variation in ratios from different sources, another aspect influencing the differences is the atmospheric lifetime and baseline atmospheric concentrations (background concentrations). The atmospheric lifetime of $PM_{2.5}$ is longer than CO, resulting in more transport opportunities for $PM_{2.5}$ and relative higher background concentrations. For example, Wang et al. (2020) reports background concentrations for $PM_{2.5}$ in Taiwan of 4.4 µg/m^3, while atmospheric concentrations for CO are normally around 0.1 ppm (UCAR, 2017). The background concentration for $PM_{2.5}$ is about 50% of the lowest GV, while that of CO is about 1%. In confined places close to combustion sources, both $PM_{2.5}$ and CO concentrations can become magnitude of orders higher than ambient concentrations. The CO concentration, however, will quickly reduce to non-problematic levels if the source is removed, and will not influence the wider surrounding as much as $PM_{2.5}$. A large $PM_{2.5}$ source, instead, can influence concentrations in the wider environment and result in a relative higher background concentration.

Besides the difference in emission ratios and atmospheric concentrations, there is also a crucial difference in health effects. For CO, these are primarily short-term (up to even 15-minutes), while those of PM are also related to long-term exposure. For these three reasons, it is relevant to study not only one of the two, but both PM and CO.

CO_2 health effects and guideline values

While CO_2 is well known as a significant factor in climate change, in relation to air pollution and health effects it is relevant as a ventilation parameter. As humans are a source of CO_2, its concentration is an indicator of the quality of the ventilation in a certain space. Atmospheric CO_2 concentrations range from 400-500 ppm. Higher concentrations can result in adverse health effects. Severe health effects of CO_2 only occur under extremely high concentrations. In 1986, at Lake Nyos in Cameroon multiple people died due to an exposure to estimated CO_2 concentrations of 8-10% (i.e., 80 000 - 100 000 ppm) (Rice, 2014); this concentration was caused by a sudden outgassing of CO_2 stored in the lake. Rice (2014) reports other adverse health effects, such as decreased lung functioning, from 8500 ppm. Such high levels, however, generally not occur when the primary source is human respiration. At lower levels of CO_2, reported effects include drowsiness, loss of attention and headaches (Soomro et al., 2019). Generally, 1000 ppm is used as a threshold to indicate that ventilation is needed. Satish et al. (2012) found that exposure to a concentration of 1000 ppm influenced decision-making performance. Between 1000-2000 ppm symptoms like drowsiness can occur, while exposures in the 2000-5000 ppm range can additionally cause headaches, sleepiness, loss of attention, and so on (Soomro et al., 2019).

Materials and methods

Student science project

Students of Water Supply and Environmental Engineering (WSEE; 139 students, Year 4) and Meteorology and Hydrology (MHD; 26 students, Year 2), Arba Minch University, Ethiopia, worked in groups of 4-6 (total 33 groups) to investigate a self-selected scenario in which they expected air pollution. The students could pick scenarios related to either CO, $PM_{2.5}$ and/or CO_2. The groups had to produce a measurement plan (and implement feedback on its draft version), before they could conduct measurements of the respective air pollutants. All measurements were conducted in November and December 2019. The first author of this article was the lecturer for the project. The three co-authors were students within the project.

Measurement instruments

The instruments available were a Lascar EL-USB-CO datalogger (for CO, range 1-1,000 ppm), a UCB-PATS+ (for $PM_{2.5}$, range 10-30,000 µg/m^3) and a IQAir Airvisual Pro (for $PM_{2.5}$, range 1-1,800 µg/m^3 and/or CO_2, range 400-10,000 ppm), which we will refer to as ELCO, PATS, and IQAV respectively. The ELCO measures CO based on electrochemistry: CO oxidizes on an electrochemical cell and is transformed into an electric current that is linearly proportional to the concentration. Measurement of $PM_{2.5}$ by the PATS and IQAV uses light scattering. The amount of scatter, which is related to the number of particles, is detected by a photodetector. The resulting voltage signal is proportional to the mass concentration. CO_2 is measured based on nondispersive infrared (NDIR) technology. The instrument has an infrared lamp and an infrared detector. CO_2 absorbs infrared light at a specific wavelength; the amount of absorption can be detected. The amount of infrared light being absorbed by CO_2 is directly proportional to the CO_2 concentration.

Both ELCO and PATS are commonly used in air quality studies with a focus on biomass burning (Chowdhury et al., 2012; Kumar et al., 2015; Leavey et al., 2015; Ochieng et al., 2016; Pennise et al., 2009; Rosa et al., 2014). The IQAV is used worldwide for indoor and ambient air quality monitoring (IQAir, 2020), though to a lesser extent in scientific studies. The measurement principles (light scatter for $PM_{2.5}$ and NDIR of CO_2) are, however, widely used in other instruments. For $PM_{2.5}$ with the IQAV, Massen et al. (2018) found a correlation coefficient with a reference instrument of 0.97. For CO_2 with an NDIR instrument (such as the IQAV), Petersen et al. (2018) found a measurement uncertainty of <50 ppm given instruments that are calibrated for temperature influences (which is the case for a -10 to 40°C range). The instruments were factory-calibrated and had not been used before the measurement project, other than for short test measurements.

Data collection procedures

For the PATS, the lecturer performed a zero-calibration before and after each measurement. The instruments were prepared and started by the lecturer. The students got the necessary instrument while it was already running. Therefore, the students only had to place the instrument at their chosen position(s). The students took the instruments for a minimum of 24 hours, to make it possible to conduct their measurements at any relevant time. The lecturer switched off the instruments after they were returned by the students and retrieved the measurement data from the instruments.

Within a measurement plan, the students described their measurement location (such as 'kitchen' or 'bus station'). For data collection at that location, the students were instructed to place the instrument at a relevant position, meaning a location which is representative of where people could realistically be exposed (for example, in the kitchen an instrument should not be placed directly above a fire, as people do not reside there). Furthermore, students were instructed to hold the measurement instrument stable at their chosen location, for example by fixing it to some construction. The students were asked to make regular notes of relevant circumstances (such as the presence of air pollution sources), and to take photos.

Quantity of measurement data

33 groups of students conducted a total of 65 measurements, with some of the groups collecting multiple measurements (for example, inside and outside a restaurant kitchen). The length of measurements ranged from 5 minutes to 5.75 hours (average and median: 1.7 hours), with measurement frequencies ranging from 10 seconds to 5 minutes. Here we include 51 of the 65 measurements. The 14 exclusions are accounted for as follows. Background and reference measurements are left out (n=11). For one group of students the measurements were disturbed by dust being blown into the sensor, so these are also omitted (n=2). Finally, one measurement was continuously at the lowest value of the instrument and so provided no analysable information (n=1). This leaves a total of 51 measurements for analysis.

Measurement locations

The 51 measurements and their locations are divided into 5 separate groups and 17 subgroups. Table 1 shows the distribution of measurements over separate locations.

Most measurements were conducted at the Main Campus of Arba Minch University (referred to as 'campus' in the remainder of this article). Measurements in restaurants were held at different campus cafeterias, and at one restaurant in Arba Minch town. Measurements at households were conducted in different homes in Arba Minch. Measurements at waste burning sites were held close (CO between 1 and 40 meters, $PM_{2.5}$ between 1 and 20 meters) to burning of domestic or agricultural waste on the campus. Ambient measurements were conducted in Arba Minch bus station, at the roadside close to campus, at two different generators in Arba Minch town, and at a smoking area on campus. CO_2 ventilation measurements were all conducted on campus: in libraries, in student dormitories, in classrooms, and in cafeterias.

Table 1: *Summary of measurement characteristics, including, per scenario, the number of datafiles (N_F), the number of data points within these data files (N_D) and the total measurement time in hours (N_H).*

ID	Scenario	Pollutant	Instrument	N_F	N_D	N_H
	Restaurants					
1A	Visitor area	CO	ELCO	5	1139	9.3
1B	Kitchen area	CO	ELCO	15	4584	24
	Households					
2A	Kitchen, wood fuel	CO	ELCO	5	415	6.8
2B	Coffee ceremony[1] inside	$PM_{2.5}$	IQAV	1	360	1.0
2C	Coffee ceremony outside	$PM_{2.5}$	IQAV	1	360	1.0
2D	Charcoal cooking outside	CO	ELCO	1	60	1.0
	Waste burning					
3A	CO	CO	ELCO	4	1020	6.9
3B	$PM_{2.5}$	$PM_{2.5}$	PATS	1	121	2.0
	Ambient					
4A	Bus station CO	CO	ELCO	1	360	1.0
4B	Bus station $PM_{2.5}$	$PM_{2.5}$	IQAV	1	243	2.0
4C	Roadside	$PM_{2.5}$	PATS	1	721	2.0
4D	Generator[2]	$PM_{2.5}$	PATS	2	698	1.9
4E	Smoking area	$PM_{2.5}$	PATS	1	1099	3.0
	Ventilation					
5A	Library	CO_2	IQAV	3	942	9.0
5B	Dormitory	CO_2	IQAV	3	547	7.8
5C	Classroom	CO_2	IQAV	2	269	3.6
5D	Restaurant	CO_2	IQAV	4	2134	9.0
	All			**51**	15 072	91

1. The Ethiopian coffee ceremony is the full process of roasting beans up to preparing and serving coffee, usually on a charcoal fire and often together with burning incense.
2. One <25 kVA gasoline generator, and one 42 kVA diesel generator.

Distinguishing priority areas

To distinguish priority areas, measurement results of the students are compared to guideline values (GVs). For all scenarios that are identified as priority area, measurement results are compared to results in other studies. In this way, the identification of priority areas is validated.

$PM_{2.5}$ priority areas

As discussed in section 2.1, the GVs for $PM_{2.5}$ are 5 µg/m³ and 15 µg/m³ for an annual and 24-hour average, respectively. All measurements are short-term (less than 24 hours). For that reason, the GV of 15 µg/m³ as 24-hour average will be used. For comparison with the GV, the measured concentration ($C_{Measured}$) is translated to a 24-hour average concentration (C_{24h}) based on a likely duration (LD) of the respective circumstance (scenarios

2B, 2C, 3B, 4D and 4E: 1 hour; scenarios 4B and 4C: 8 hours), and an assumed background concentration (CBackground), as shown in equation 1. A background concentration of 0 µg/m³ is used, so that the calculated average concentration can be fully attributed to the measurement.

$$C_{24h} = \frac{C_{Measured} * LD + C_{Background} * (24 - LD)}{24} \quad (1)$$

CO priority areas

As discussed in section 2.2, GVs for CO are 87, 52, 26 and 9 ppm for time averages of respectively 15 minutes, 30 minutes, 1 hour and 8 hours. For distinguishing priority areas related to CO, all available time averages from the measurement data are used for comparison (for example: a measurement period of one hour provides four 15-minute averages, two 30-minute averages and one 1-hour average, each of which can be compared to the respective GV). To compare each of these GVs equally, measurement results for the respective time periods are also shown as percentages relative to their perspective GV. For example, measurement results of 87 ppm as 15-minute average and 52 ppm as 30-minute average are both presented as 100%.

CO_2 priority areas

For distinguishing priority areas related to CO_2, a guideline value of 1000 ppm will be used, as discussed in section 2.4. For CO_2, the averages of the measurements are compared to the GV.

Data analysis

For CO_2, a disruption of the measurements could occur if the group members breathed close to the sensor. While the students were warned for this, some groups acknowledged that this happened. Such a moment can be recognized by a sudden and extreme increase of the concentration, resulting in outliers. Outliers are operationalized as values higher than mean+2* standard deviation (Std), whose removal results in a more than 10% change in mean concentration. Outliers were found in and pruned from three datafiles.

All measurement data is processed with Python version 3.7.9 (Python Core Team, 2020), and all graphics are created with the Python library Matplotlib version 3.3.2 (Hunter, 2007). The data generated and/or analysed during the current study (air quality measurement data and python scripts) are available in the OSF repository, https://doi.org/10.17605/OSF.IO/HW57Z.

Results

$PM_{2.5}$ measurements

Priority areas

Table 2 shows the measurement results for the scenarios with $PM_{2.5}$ measurements. Besides the mean, the highest 10-minute average is shown to give insight in the degree of variation. Figure 1 shows each of the $PM_{2.5}$ measurements, translated into a likely 24-hour average, in comparison with the guideline value.

Table 2: *Mean, standard deviation (Std) and highest 10-minute average for $PM_{2.5}$ measurements.*

ID	Scenario	Mean (Std)[1] [µg/m³]	Highest 10 min. [µg/m³]
2B	Coffee ceremony inside	>606	>1419 [2]
2C	Coffee ceremony outside	>298	>1293 [2]
3B	Waste burning	1052	2145
4B	Bus station	94	296
4C	Roadside	39	146
4D	Generator	730 (679) [3]	1890
4E	Smoking	149	802

1. If there are multiple measurements for one scenario, the standard deviation is shown, based on the means of the different measurements.
2. Measurements with the IQAV reached the instrument's upper limit of 1800 µg/m³ during the coffee ceremonies. Therefore, concentrations were most likely higher than reported
3. Students measured at two different generators: a gasoline and a diesel generator (see Table 1 note 2). Individually, average measurements were respectively 52 and 1409 µg/m³.

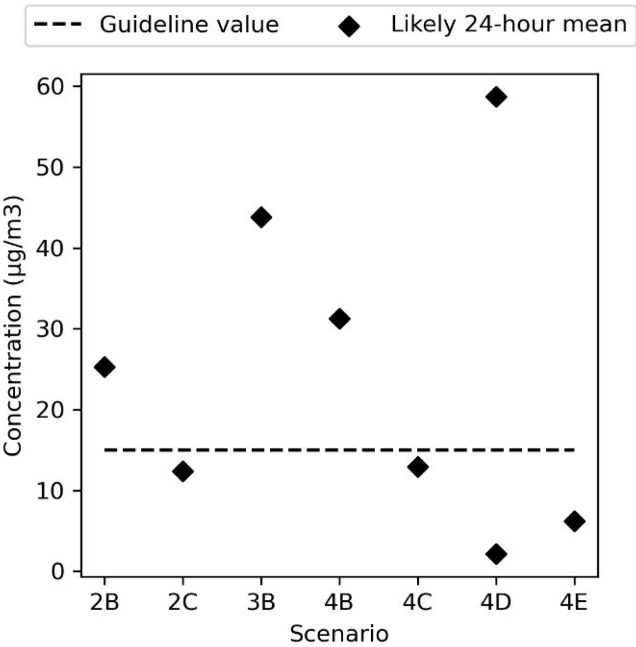

Figure 1: *Likely 24-hour average concentrations for all $PM_{2.5}$ measurements, in comparison with the guideline value.*

The highest concentration peaks (10-minute averages higher than 1000 µg/m³) are witnessed at the coffee ceremonies, close to waste burning and close to a generator. The highest mean concentration is reported close to waste burning – though concentrations at the coffee ceremonies might also have been higher (see Table 2 note 2). Exceedances of the guideline value are expected at the inside coffee ceremony (2B), close to waste burning (3B), at the bus station (4B) and close to a generator (4D). Based on these measurements, those scenarios can be considered priority areas for research.

Comparison with earlier studies

A pilot study on coffee ceremonies inside in 10 houses in Addis Ababa, Ethiopia, found PM_4 concentrations ranging from <720-

4,200 µg/m³ (Keil et al., 2010). By definition, PM_4 is slightly higher than $PM_{2.5}$ (PM_4 consists of $PM_{2.5}$ and all particles with an aerodynamic diameter of 2.5-4 µm), and the lower limit of the instrument used by Keil et al. is 720 µg/m³. However, these higher measurements confirm the assumption that concentrations were higher than reported. More importantly, it provides converging evidence for our designation of indoor coffee ceremonies as a priority area for further research.

Some studies have measured under circumstances of open waste burning. However, these studies concern burning at a larger distance or burning in a large area (for example (Bulto, 2020), with respect to a whole city). No earlier study reports measurements close to (<40 meter) open waste burning. Sivertsen (2006) reports different emission factors for $PM_{2.5}$ and PM_{10}, as well as 20-meter distance modelled PM_{10} concentrations. Based on the ratio in emission factors, modelled $PM_{2.5}$ concentrations are 622–1110 µg/m³. This corresponds with the measured concentration by the students, and the conclusion that open waste burning is a priority area.

$PM_{2.5}$ measurements at different bus stations in two studies ranged from 49–223 µg/m³ (Cheng et al., 2011; Salama et al., 2017); the students' measurements fall within this range. Considering $PM_{2.5}$ concentrations at the bus station as a priority area is valid.

Two studies conducted close to smaller (<25kVA) gasoline generators measured 83 and 86 µg/m³ respectively on average (Giwa, Nwaokocha, & Samuel, 2019; Oguntoke & Adeyemi, 2017). Variation amongst the generators however ranged from 7.9–309 µg/m³. Our finding of 52 µg/m³ close to a smaller gasoline generator corresponds to this range. One study measured concentrations close to diesel generators <500 kVA, of 221-492 µg/m³ (Giwa, Nwaokocha, & Adeyemi, 2019). The students' measurement result of 1409 µg/m³ close to a diesel generator is much higher. This might be because Giwa et al. started measuring only after the generators had run for 30 minutes (ignoring higher start-up concentrations), as well as that the upper limit of their instrument is 500 µg/m³. Setting the upper limit aside, we also witnessed higher start-up concentrations. Without the first 30 minutes, the average measured concentration is 857 µg/m³ instead of 1409 µg/m³. The rationale by Giwa et al. is that the bigger diesel generators generally run for lengthy periods of time, implying that the start-up period is not representative. This is not the case for the generator at which the students measured, which is only used during power cuts – which sometimes take only some minutes. Therefore, viewing pollution from a diesel generator (especially during start-up) as a priority area, based on the students' measurement, is valid.

CO measurements

Priority areas

Table 3 shows the measurement results for the scenarios with CO measurements, with mean values as well as maximum concentrations for time averages corresponding to the guideline values. Figure 2 shows all measured 15-minute, 30-minute and 1-hour averages, relative to the respective guideline value.

Table 3: *Mean, standard deviation (Std), and highest 15-min, 30-min and 1-hour average, both as concentration and relative to their respective guideline value.*

ID	Scenario	Mean (Std)[1] [µg/m³]	Highest 15-min. [ppm] (% of GV)	Highest 30-min. [ppm] (% of GV)	Highest 1-hr. [ppm] (% of GV)
1A	Visitor area	8.2 (7.0)	36 (41%)	30 (58%)	27 (102%)
1B	Kitchen area	37 (40)	336 (386%)	236 (454%)	177 (682%)
2A	Kitchen, wood fuel	16 (9.9)	36 (42%)	35 (68%)	18 (69%)
2D	Charcoal outside	55	120 (138%)	88 (170%)	-
3A	Waste burning	18 (16)	84 (97%)	72 (138%)	13 (50%)
4A	Bus station	0.7	2 (2%)	1 (2%)	-

1. If there are multiple measurements for one scenario, the standard deviation is shown, based on the means of the different measurements.

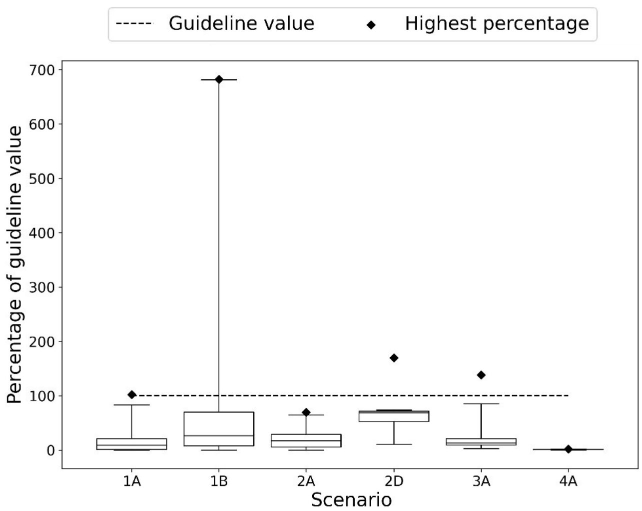

Figure 2: *Boxplot of all 15-minute, 30-minute and 1-hour averages measured by students, together with the highest value and the guideline value. Whiskers of the boxplots extend to the minimum and maximum value.*
Note: *The 'Highest percentage' value can be higher than the values in the boxplot. For example, in the boxplot, for one hour four 15-minute averages are shown, while for the highest value, the maximum out of a list of 45 rolling averages within that hour is selected.*

Highest CO concentrations are measured in the kitchen areas of restaurants, and close to charcoal burning outside. From Figure 2 it can be observed that especially in the kitchen areas of restaurants (1B), exceedances of the guideline values are witnessed. However, also in the visitor's area (1A), close to outside charcoal cooking (2D) and close to waste burning (3A) exceedances are measured. These scenarios can be considered priority areas for research.

Comparison with earlier studies

We are not aware of prior studies conducting CO measurements in restaurant kitchens or visitor areas that have a dominant use of biomass fuels. Within barbecue restaurants (charcoal barbecues in both kitchen and visitor area, but also gas appliances are used), concentrations are measured of 12.3 (range 2.6-22.5) and 21.1 (range 3.2-42.6) ppm CO, respectively (Zhang et al., 2017). While our measurements in visitor areas are comparable, measurements in the kitchen area are higher. This is to be expected due to the dominant use of biomass. It is valid to view these areas as priority areas.

No other studies were found with measurements of CO close to charcoal cooking outside, or close to (<40 meter) open waste burning. These areas should be viewed as priority areas, based on our measurement results in combination with no invalidation.

CO_2 measurements

Priority area

Table 4 shows the measurement results for the scenarios with CO_2 measurements. Besides the mean, the highest 10-minute average is shown to give insight in the degree of variation. Figure 3 shows each of the CO_2 measurements in comparison with the guideline value.

Table 4: *Mean, standard deviation (Std) and highest 10-minute average for CO_2 measurements.*

ID	Scenario	Mean (Std) [ppm]	Highest 10 min. [ppm]
5A	Library	740 (185)	1389
5B	Dormitory	1753 (584)	4119
5C	Classroom	575 (36)	673
5D	Restaurant	560 (41)	884

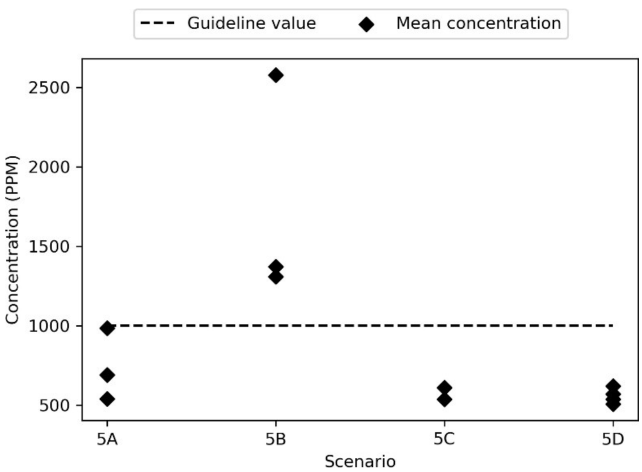

Figure 3: *Average concentrations for all CO_2 measurements, in comparison with the guideline value.*

Highest concentrations overall are measured in dormitories. The mean concentration in libraries, classrooms and restaurant did not exceed the guideline value of 1000 ppm, though the highest 10 minutes in libraries slightly exceeded this. Based on the averages of the individual measurements, all three measurements within the dormitories were above the guideline value, making this a priority area.

Comparison with earlier studies

Jenkins (2018) reports measured CO_2 concentrations ranging from 650-2900 ppm in student dormitories on an American college campus. The student measurements correspond with this range. It is valid to view dormitories as a priority area.

Discussion

Scenarios measured, but not appointed as priority area

For some of the scenarios, measurements by students did not reveal exceedances of the guideline value. For $PM_{2.5}$, this was the case for measurements at an outdoor coffee ceremony (2C), the roadside (4C) and a smoking area (4E). As discussed in Table 2 note 2, concentrations were likely higher during the coffee ceremony measurements. There is however not another study with measurements at outdoor coffee ceremonies to validate the result, and it is at least logical that an outdoor coffee ceremony results in lower concentrations than indoor. While traffic close to Main Campus (the environment for the students in this study) is not dense, for other campuses closer to busier roads concentrations at roadside might be different. For smoking, two earlier studies found average concentrations of 124 and 131 $\mu g/m^3$ (Brauer & Mannetje, 1998; Williams Jr et al., 2014), which is quite similar to the students' measurement of 149 $\mu g/m^3$. Whether the guideline value is exceeded or not of course depends on the assumed exposure duration of 1 hour – if this is longer, the GV can be exceeded.

For CO, no exceedances were measured in household kitchens using biomass fuel (scenario 2A) and in the bus station (scenario 4A). Earlier studies within household kitchens using biomass fuel report average concentrations of 7.9 (Clark et al., 2010), 7.8 (Khalequzzaman et al., 2011), 22.3 (Leavey et al., 2015) and 7.5 (Mukhopadhyay et al., 2012) ppm, which is in the same order of magnitude to the student measurement average of 16 ppm, suggesting that the student measurements are not uncommonly low. In those studies, however, a large variation was witnessed, with certainly also some exceedances of the guideline values. More importantly, however, most studies also measure $PM_{2.5}$ in such circumstances, with much higher exceedances of the guideline value. Household kitchen areas with biomass fuel therefore still might be a priority area, even though it did not follow from this study. As for CO concentrations in a bus station, Salama et al. (2017) report concentrations of 8.5 ppm on average (range 6.5-9.8 ppm). While this is higher than the concentration measured by students, it supports the finding that this is not a priority area.

For CO_2, no exceedances were measured in libraries, classrooms, and restaurants. No prior work can be found on CO_2 measurements in libraries, but our preliminary measurement presents no special cause for alarm. For classrooms, Soomro et al. (2019) report several measurement results ranging from 478-4093 ppm. The student measurements at 575 ppm fall towards the low end of this range, but not outside it. For restaurants, Zhang et al. (2017) reports concentrations of 400-890 ppm, while Akbar-Khanzadeh et al. (2002) found concentrations of 618-1835 ppm. Again, student measurements of (on average) 560 ppm fall towards the lower end of the range found in these studies combined.

Missing scenarios

Although our study presents a range of first-time measures and replicates others, it does not represent an exhaustive sampling. For one thing, for some scenarios either $PM_{2.5}$ or CO was measured, while both components might be relevant. CO values close to a coffee ceremony have never been subject of a study before. As for generators, an earlier study close to gasoline generators found CO concentrations of 141-4167 ppm (Oguntoke & Adeyemi, 2017), while a study close to diesel generators found concentrations of 19-198 ppm (Giwa, Nwaokocha, & Adeyemi, 2019). CO measurements close to generators might, therefore, certainly be relevant. Similarly, with high CO values in restaurant kitchens, high $PM_{2.5}$ values can be expected, and $PM_{2.5}$ concentration measurements in household kitchens with biomass fuel or close to charcoal cooking outside are also relevant.

Furthermore, there might be scenarios entirely lacking. Given the embedding of this project in coursework on campus, students privileged scenarios to which they had easy access, such as the campus and its surroundings. Students not based on campus or still living at their family homes are exposed to other scenarios in which measuring air quality would be relevant. Here we see opportunities for the crowdsourcing methods we have pioneered. Many of the measurement devices are portable and easy to operate, and so could feasibly be carried into a wider range of scenarios. Still, the priority areas identified in this study represent scenarios in which many students commonly find themselves, and they therefore provide ample room for further research.

This leads to a recommendation. Future student science projects might challenge students to select scenarios different from the ones that have been part of this study. Students can conduct preliminary measurements in similar scenarios for the component that was not yet measured (such as CO during a coffee ceremony), or they might come up with entirely new scenarios.

Concentration and exposure

While students have measured concentrations, duration of exposure is another key variable determining health effects. The conditions of our study, in which we privileged short-term measurements in a wide range of localities, did not allow us to systematically investigate duration of exposure. For $PM_{2.5}$, this study estimated a likely duration. For a better quantification of exposure and a thorough investigation of related health effects, specific attention needs to be paid to the duration of exposure for different people across a range of circumstances. Even without a systematic measure of duration of exposure, however, it is already clear that several of the priority areas are likely to cumulatively present a likelihood of adverse health effects. An individual's exposure is usually not incurred in one individual setting but results from a sequence of settings. Students might encounter open waste burning, a running generator, a coffee ceremony, and biomass cooking, all within the same day. For a more thorough evaluation of exposure, it is recommended to collect additional metadata on duration and frequency of the circumstances under which people are exposed.

Conclusion

If air pollution represents one of the biggest current threats to human health, maximizing opportunities for measurements in a wide range of human environments is of paramount importance. Here we have presented the use of a Student Science (citizen science by students) approach towards this goal, with novel empirical and methodological contributions. Empirically, we report a unique set of first-time measurements of $PM_{2.5}$, CO and CO_2 in a range of settings that are woefully understudied despite being a common part of people's surroundings worldwide. Our $PM_{2.5}$ measurements showed a likely exceedance of the guideline value during inside coffee ceremonies, close to open waste burning, at a bus station, and close to a diesel generator. For CO, extreme values in excess of guideline values were measured in restaurant kitchens as well as in restaurants' visitor areas, close to outdoor charcoal cooking, and close to open waste burning. For CO_2, values higher than the guideline value were measured in dormitories. Collectively, these settings, several of which are reported here for the first time, can be considered priority areas for further research.

Methodologically, our study has illustrated the benefits of the Student Science approach by crowdsourcing air quality measurements in a participatory research setting. Such forms of citizen science may provide partial solutions to structural inequalities in resources that dictate research interests and may bring large-scale collection of key measurements within reach. The Student Science approach also has the twin benefits of furthering students' education while producing measurements of high scientific and societal value.

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Author contributions

Johannes Dirk Dingemanse: Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project administration. **Muse Abayneh Abiyu, Kirubel Getachew Tesfaye and Feyera Fekadu Roro**: Methodology, Investigation, Writing – Review & Editing.

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Research article
Conceptualising air quality management instruments in South Africa

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Abstract
South Africa has developed a plethora of air quality management instruments as a means to address and mitigate air quality challenges. However, no holistic conceptualised understanding of these instruments exists to critically inform air quality management and governance. The aim of this paper is to identify existing air quality management instruments and conceptualise them in terms of three broad environmental management approaches, namely Command and Control-based (CaC), Fiscal-based and Civil-based. This allows for a critical understanding of the overall air quality governance framework in South Africa. A literature review methodology was followed to identify the different instruments. The research results suggest an over reliance on CaC, high levels of hybridisation, high level of complexity and an overall lack of synergy between instruments. The research notes that even amidst the plethora of instruments South Africa continues to face serious air quality challenges. We hope that the conceptualisation provided in this paper provides a basis towards a more detailed analysis of the strengths, weaknesses, and performance of different approaches and instruments to ensure more effective air quality governance and management in South Africa.

Keywords
air pollution, air quality management, instruments, environmental management, conceptualise, command and control (CaC), fiscal-based, civil-based, agreement-based.

Introduction
Internationally ambient air quality (AQ) has deteriorated significantly, in part due to human activities that release pollutants into the atmosphere (Kuklinska et al. 2015, Miranda et al. 2015, Sinha 2018). It is estimated that the global particulate matter ($PM_{2.5}$) concentrations have increased by 37.5% over the period 1960 to 2009 which were dominated by increases from China and India as a result of economic expansion and growth in emissions (Butt et al. 2017). In South Africa, poor local ambient air quality has become a major concern due to negative health impacts that directly affect mostly poorer communities relying on coal and wood burning for household fuel and who are also residing close to polluting industries (Dugard and Alcaro 2013).

In response to air pollution impacts, governments have been working with research institutions, industry and civil society to introduce efficient management measures (Ma et al. 2019). Many countries including China, United States (US) and the European Union (EU) have implemented a series of national control policies to reduce air pollution emissions (Wang et al. 2014, Kuklinska at al. 2015). At local level, European cities, where the majority of Europeans reside, have also developed various policy instruments such as air quality plans. These plans include emission abatement measures designed and implemented by EU Member States (MS) in accordance with the Framework Directive 96/62/EC on ambient air quality assessment and management (Miranda et al. 2015).

The South African government has a long history of developing and implementing air quality management policies and legislation, dating back to the 1960s. These policies and legislations have over time introduced various regulating instruments to inform air quality governance decision-making (Emilson et al. 2004). Moreover, various air quality management approaches and instruments have been introduced by industry and civil society to improve their performance and protect their interests. The result has been a highly complex air quality management and governance context. However, despite a plethora of air quality management instruments, no integrated framework and/or conceptualisation of these instruments exists. Such a framework is needed to critically consider the overall air quality management and governance context in South Africa. Ideally, a management and governance system with high levels of hybridisation and subsequent redundancy should be achieved. This will deliver an integrated and balanced approach to air quality management.

Therefore, the aim of this paper is to identify existing air quality management instruments and conceptualise them in terms of broader environmental management approaches (Nel and Alberts 2018) with a view to gain a critical understanding of the overall governance framework for air quality management in South Africa.

Methodology

To identify the different air quality management instruments, this research applied a literature review methodology. Air quality management cuts across various disciplines which means that a wide range of possible literature sources are potentially relevant. Snyder (2019) argues that literature review as a methodology is one of the best ways of engaging at a higher theoretical and conceptual level. Moreover, it also reveals areas where more research is required, which is an important component of creating theoretical frameworks and building conceptual models.

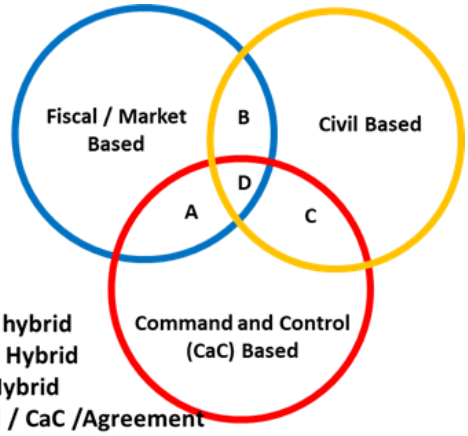
This study followed a similar data collection approach as Olagunju et al. (2019) in which a literature review was done through a broad systematic search of popular academic electronic databases such as Google Scholar, and Scopus. Other non-peer reviewed literature such as relevant legislations were located from general Google searches, textbooks and specific databases such SAAQIS and Center for Environmental Rights (CER) library databases. These databases were searched using the keywords 'air quality management' AND 'South Africa' AND 'Environmental management instruments'. Ultimately a saturation point was reached where the authors could not find any new relevant literature from their searches. An earlier version of this paper was presented at the National Association of Clean Air (NACA) Conference in November 2020 and was published in its Proceedings.

Environmental Management policy instruments

Internationally, researchers from different countries have classified environmental policy instruments into several different categories. Kemp (1995) categorises them into command, market, and communication types, while Hamilton et al. (1997) categorises them into market-utilised, market-established, environmental regulation, and public mobilisation types. Howlett and Ramesh (2009) categorised the policy instruments by the required level of government involvement as mandatory, hybridised, and voluntary policy instruments. According to Liang et al. (2018) the classification by Howlett and Ramesh (2009) is internationally the most widely accepted and adopted within the field of environmental management.

In South Africa, environmental management and governance instruments are generally classified according to the following broad approaches: a) Command and Control-based approaches (CaC), b) Fiscal/Market-based approaches, c) Civil-based approaches as shown in figure 1 (Nel and du Plessis 2001; Nel and Alberts 2018). However, many instruments reflect characteristics of more than one approach. In such instances these instruments are referred to as hybridised instruments. An example would be environmental taxes that are based in law (CaC) but might also present a fiscal incentive (Fiscal-based).

Sometimes so-called 'Agreement based approaches' are included as a separate classification. However, for this paper we have opted to integrate agreement-based approaches with the other three approaches (as shown in figures 1 and 4 letter D). Because of the high level of hybridisation, we consider this to be a more accurate conceptualisation as will be discussed in the following sections. The different instruments are employed by both government and private sector to achieve environmental policy goals and/or typically more sustainable outcomes.



A = Fiscal / CaC hybrid
B = Fiscal / Civil Hybrid
C = Civil / CaC Hybrid
D = Fiscal / Civil / CaC /Agreement Hybrid

Figure 1: *Environmental management instruments in South Africa including hybrid approaches (A-D).*

The following sections provide a more detailed discussion of each approach.

Command and Control-based approach

These approaches include instruments that are mandated through policy and legislation. These instruments are typically refined through regulations and environmental standards designed to achieve specific environmental objectives (Kostka 2016). The legislation and regulations are set by governmental authorities to regulate activities and human interaction with the environment towards minimising potential impacts on the receiving environment (Malloy 2010). Command and Control instruments regulate industries by enforcing universally applicable environmental laws and therefore often face criticism from industry for being inflexible (Stavins 2000; Kirschke and Newig 2017).

The CaC instruments dealing with air quality in South Africa emanate from different pieces of legislation within the South African legal framework starting with section 24 of the Constitution of the Republic of South Africa which is the supreme law in the country that informs all other legislation (see figure 2). The constitution makes provision for the citizen's rights to an environment that is not harmful to their health or well-being. The National Environmental Management Act (NEMA) is the next level framework legislation that provide for cooperative environmental governance as well as defining the principles for decision-making on matters affecting the environment. NEMA provides that reasonable legislative (CaC) and other measures (Fiscal and Civil based) be implemented to address environmental issues including air quality.

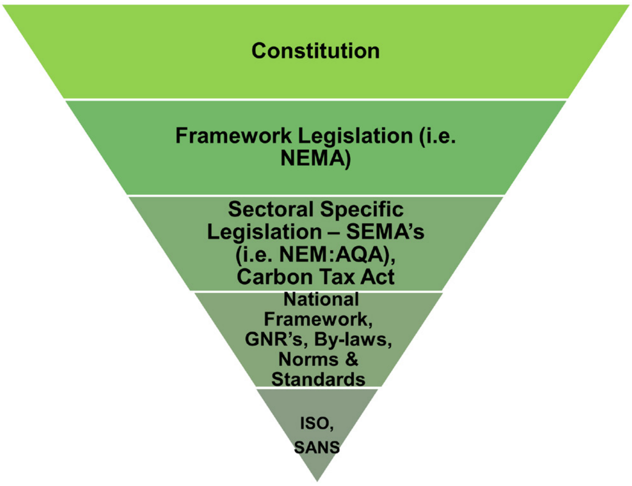


Figure 2: *South African air quality legal framework.*

The next level of legislation is sectoral specific acts or the so-called 'Specific Environmental Management Acts' (SEMA's) related to specific areas of concern such as air quality. Although air quality CaC instruments originated from the Atmospheric Pollution Prevention Act no. 45 of 1965 (APPA) which made provisions to control certain industrial processes (Scorgie 2012), the APPA became outdated after 1994, particularly relating to assigning of roles and responsibilities to the different spheres of government (Engelbrecht & Kornelius 2015). The National Environmental Management Air Quality Act No. 39 of 2004 (NEM:AQA) came into effect in 2005 as sector-specific legislation for managing and governing air quality by all relevant spheres of government. NEM:AQA consists of nine chapters which provides several governance instruments or measures that were not previously included in the APPA such as ambient air quality standards (see table 1) (Naiker et al. 2012).

The main objective of NEM:AQA is "To protect the environment by providing reasonable measures for the protection and enhancement of the quality of air; the prevention of air pollution and ecological degradation; and securing ecologically sustainable development while promoting justifiable economic and social development, and to give effect to section 24(b) of the Constitution".

Furthermore, there are several other pieces of national legislation, as shown in appendix A, that are directly or indirectly linked to the management of air quality. The 2017 National Framework for Air Quality Management in the Republic of South Africa is an important policy document that also provides for various CaC interventions.

Engelbrecht and Kornelius (2015), further denotes that municipal air quality management by-laws are also an important regulatory instrument in the context of air quality. Chapter 7 of the constitution read with section 13(a) of the Municipal Systems Act and section 11(1) of NEM:AQA, specifies that at a local level, municipalities must adopt air quality by-laws (Engelbrecht & Kornelius 2015). Appendix A includes additional municipal acts and policies such as the Municipal Systems Act and Carbon Tax Act with relevance to air quality management.

Table 1: *Command and control instruments for air quality management with relevant examples.*

Command & Control Instrument	Source/Example
Air quality law	See Figure 2 and Appendix A
Inspections	NEM:AQA Chapter 5
Requests for more information	NEM:AQA Chapter 2 s.7 ss. 2
Audits	NEM:AQA s. 45
Prosecutions	NEM:AQA s. 52
Authorisations, permits, licences, etc.	NEM:AQA Chapter 5 s.37 & s.38
Directives, Interdicts, Restraining orders, Liability reforms	NEM:AQA s. 51
Orders and Penalties	NEM:AQA s. 51 and 52
Statutory record-keeping and reporting	NEMA s.30
Environmental/Air Quality standards	National Ambient Air Quality Standards
Model bylaws	Constitution Section 156(1)(a)(e.g. Cape Town Air Quality Management By-law, 2016)
Environmental restoration orders	NEMA s28

Fiscal-based approach

The fiscal-based instruments, also known as market-based instruments, focus more on the market or price mechanism to change behaviour and or support environmental management through for example, taxes, subsidies, and permits (Wessesls and Mkhari, 2007; Pirard 2012). These instruments rely heavily on incentives and disincentives and aims to attach economic value to environmental services such as clean air. This approach encourages organisations and consumers to consider more environmentally friendly and cost-effective measures in their operations and products (Munda et al. 1994; Stavins, 2010). Previous studies have shown that companies are more willing to partake in environmental initiatives that incentivise certain goals and are willing to alter certain aspects and behaviour of the business to meet these goals (Frondel et al. 2008). Fiscal based instruments are more flexible than the traditional CaC

Table 2: *Policy matrix of interventions to correct for environmental market failure (Source: National Treasury 2006)*

Using markets *(using existing prices)*	**Creating markets** *(forming new markets and marketable goods)*	**Environmental regulations**	**Engaging civil society**
• Elimination of perverse subsidies; • Environmentally related taxes; • Deposit-refund systems; • User charges; and • Targeted subsidies	• Property rights and decentralisation; • Tradable Permits and rights; and • International offset systems	• Product and process standards; • Bans / prohibitions; • Non-tradable permits and quotas; • Zoning; and • Liability and performance bonds	• Public participation; • Information disclosure; and • Voluntary agreements

Table 3: *Fiscal-based instruments for air quality management with relevant examples:*

Fiscal-based Instrument	**Examples**
Incentives and awards	• Clean Development Mechanism (CDM) projects e.g. Beatrix mine methane project for electricity generation. • General Fuel Levy (petrol, diesel, biodiesel), Aviation Fuel Levy. • Carbon emission tax for vehicles that produce more than 120g/km and are taxed at a rate of R75 + VAT for every g/km in excess of the 120g/km threshold. • Green procurement strategies for the City of Cape Town and Nelson Mandela Bay metropolitan municipalities. • RECSA is the association of Voluntary REC market participants in South Africa. All active producers, traders and consumers of RECs in South Africa are automatically members of RECSA.
Information disclosure programmes	
Demand-side management	
Disincentives	
Tradable Renewable Energy Certificate (TREC)/ Tradable/marketable permits	
Depository return schemes	
Security deposits	
Air Quality charges/levies	
Emission Trading Schemes/ Cap and Trade Instruments including restrictions	
Pricing policies	
Differential indirect taxes	
Tax concessions	
Subsidies (investment, research and development, activity)	
Product charges/taxes	
Resource charges/taxes	
Emission charges	
Process charges/taxes	
Two-tier tariffs	
Deposit-refund system	
Green purchasing	
User fees	
National environmental fund/account	

Table 4: *Civil based instruments for air quality management with relevant examples.*

<table>
<tr><th>Civil-based Instrument</th><th>Examples</th></tr>
<tr><td>Education</td><td rowspan="17">• Basa njengo Magogo project;
• South Durban Community Environmental Alliance campaign;
• Tree planting and rooftop gardens campaigns (e,g. Arbor Week)
• Centre for Environmental Rights (CER)
• GroundWork and the Vukani Environmental Justice Movement V Government case for the Highveld Priority Area (HPA);
• Richards Bay Clean Air Association (RBCAA)
• The case of Tergniet and Toekoms Action Group v Outeniqua Kreosootpale (Pty) Ltd;
• Uzani Environmental Advocacy CC and BP Case;
• Labelling schemes - such as energy efficiency labels on electrical appliances or organic farming produce;
• Information disclosure programmes - such as the Toxic Release Inventory in the United States or Indonesia’s PROPER initiative;
• Rating and ranking - where the environmental performance of a firm is ranked or rated according to certain criteria and publicly made available through the stock exchange for example.</td></tr>
<tr><td>Public awareness</td></tr>
<tr><td>Carbon sequestration</td></tr>
<tr><td>Public participation</td></tr>
<tr><td>Improved access to information:
– Requests for more information
– Statutory record-keeping and reporting</td></tr>
<tr><td>Air quality Monitoring Committees/Forums</td></tr>
<tr><td>Increased locus standi</td></tr>
<tr><td>Environmental justice organisations</td></tr>
<tr><td>Class action, improved access to courts</td></tr>
<tr><td>Private prosecution</td></tr>
<tr><td>Beneficial cost awards</td></tr>
<tr><td>Protection of workers</td></tr>
<tr><td>Protection of whistle blowers</td></tr>
<tr><td>Green rights</td></tr>
<tr><td>Eco-labelling</td></tr>
<tr><td>Public waste and pollution inventories</td></tr>
<tr><td>Information disclosure programmes</td></tr>
</table>

instruments in that they provide organizations and individuals the opportunity to react quickly to financial incentives and disincentives (Toxopeüs and Kotzé, 2017). For example, in the US more flexibility and greater financial incentives resulted in air pollution reduction beyond what clean air laws and traditional CaC rules require (Lurmann et al. 2015).

This approach does however also receive criticism due to environmental services not necessarily matching the economic value which is attached to them in taxes and subsidies (Pirard, 2012). Generally, any country’s market (particularly concerning environmental goods and services) can be subjected to failure at any given time which usually leads to the inconsideration of environmental issues in everyday market activities (National Treasury 2006). Under such circumstances, the South African government has developed several environmental policy interventions in an attempt to correct for environmental market failures which are dominated by regulatory instruments such as standards, bans on the use of certain goods or technologies, liability payments (such as the mining rehabilitation fund) and non-tradable permit systems as shown in table 2. It is however evident that many of the fiscal-based instruments exist as a hybrid with other approaches, particularly CaC, which are further discussed in the following sections – see table 3 for a summary.

Lastly, a number of stand-alone instruments have been identified in the literature review such as the Clean Development Mechanism (CDM) and Green Infrastructure projects which aim to, through the market mechanism and incentives, reduce emissions in developing cities and encourage green building developments.

Civil-based approach

Civil-based instruments are used to empower civil society to become key stakeholders in environmental governance and active participants in the decisions that may impact the environment and people’s health and well-being (Toxopeüs and Kotzé, 2017). Toxopeüs and Kotzé, (2017) further point out that civil-based instruments enable and empower civil society, particularly the disadvantaged, to pursue environmental justice by raising their environmental concerns to be considered in decision making by government and the private sector. Civil-based instruments aim to as a minimum inform and educate communities on the relationship between them and their environment (Keen et al. 2005). This social learning approach creates opportunities for building of partnerships and implementation of joint programmes between communities, government and industry (Keen et al. 2005). Civil-based instruments require success factors such as access to information and education, public awareness raising, legal empowerment and access to courts as well as public information inventories on for example AQ and pollution (Cooke and Corbo-Pekins, 2018).

In South Africa however, the civil-based approach is often difficult to implement mainly due to formal education being limited in most communities which then limit the potential for environmental education (Wessels and Mkhari, 2007). Also, air quality issues are very costly and complex which makes civil instruments difficult to implement.

Similar to market-based instruments, Civil-based instruments are also designed as hybrids with other approaches particularly the CaC approach. Various sections in NEMA (CaC) require public participation (Civil) to be conducted for activities that require environmental authorisations (i.e. atmospheric emission licenses) before commencement. This process is used to help incorporate public concerns and promote environmental justice in development projects and decision making (Viljoen 2007).

As shown in table 4, several air quality-related civil based instruments in South Africa rely heavily on access to information, justice campaigns, awareness and carbon sequestration campaigns.

Non-government organizations such as the Centre for Environmental Rights (CER) also play a significant role in the implementation of civil-based instruments in South Africa. The CER is comprised of a group of activist lawyers who assist communities and civil society organisations realise their Constitutional right to a healthy environment by advocating and litigating for environmental justice.

Agreement-based approach

Agreement based instruments (also known as voluntary agreements - VAs) are collaborative arrangements between the private sector, regulators, and other interested and affected parties where parties voluntarily commit to goals and actions that improve environmental performance (Delmas and Terlaak, 2001). Agreements can be used by organisations as a strategic instrument to adhere to their compliance obligations, develop new air quality management competencies ahead of competition, and communicate their responsible performance to their interested and/or affected parties (Delmas & Terlaak, 2001).

According to Farina 2001, Agreement-based instruments can be divided into self-regulation where industry will choose to set their own environmental objectives and indicators, as well as co-regulation where the environmental objectives and methods of achieving the objectives are defined through interaction between government and industry. Nel & Wessels, (2010) further argue that the adoption of VAs as self-regulation may be entirely voluntary meaning that performance is never verified by anybody, while others may need to be regularly verified (co-regulation) by independent and competent third parties. Such verifiers could also be either entirely independent such as accredited certification bodies or even enforcement agencies themselves. The verifiers could also be public watchdog bodies or enforcement surrogates appointed by the regulated (Nel and Wessels, 2010). A good example of co-regulation is the agreements organisations have with government on the collective efforts to minimise air quality impacts. These goals are put in air quality management plans (AQMP) implementation plans and are monitored. Another co-regulation agreement is the partnership between IBM with CSIR and the City of Johannesburg municipality to use the Internet of Things (IoT) to curb air pollution in the city by analysing historical and real-time data from environmental monitoring stations across the Gauteng Province. The objective was to uncover greater insight about the nature and causes of air pollution and model the effectiveness of intervention strategies. In this project, scientists are using historical and real-time data from environmental monitoring stations and machine learning and cognitive models to provide insight about air pollution, ground level ozone, and air quality to model the effectiveness of intervention strategies (IBM 2016).

Essentially agreement-based instruments exist in hybrid with other instruments in dealing with air quality issues and do not exist as a stand-alone approach as shown in figure 4 letter D. This approach helps to not focus on air quality impacts in isolation but on the interplay between all environmental impacts of an organisation which then helps to avoid duplication of impacts mitigation and saving costs.

In South Africa, the hybrid approach between voluntary agreements and CaC instruments is required under section 35 of NEMA in which an environmental management cooperative agreement (EMCA) may be entered into between the government and any person or community in order to give effect to the NEMA principles (Farina, 2001). These agreements may be entered either as negotiations between an industrial sector and government or as a result of interaction between individual polluters and affected parties such as local communities and NGO's (Farina, 2001).

It is often difficult to have a single coordinated management approach with agreement-based instruments as different companies have adopted different instruments that suit their business needs. Some of these organisations may sometimes not want to disclose their agreements to the public or to other organisations for various reasons. However, for those organisations that adopt agreement-based instruments, there are general key benefits associated with this approach. This includes: to encourage a proactive cooperative approach from the industry which can reduce conflicts between regulators and industry; allows greater flexibility and freedom to find cost-effective solutions that are tailored to specific conditions, and the ability to meet environmental targets more quickly due to decreased negotiation and implementation lags (CSIR, 2016).

The most commonly used voluntary self-regulation agreement instruments in South Africa especially in the private sector and internationally are the ISO series guidelines developed by the International Organization for Standardization (ISO) (see Figure 3). The ISO standards are adopted by various organizations including some regulations as best practice guidelines for air quality and environmental management. The ISO 14000 family of standards provide a guideline or framework for organizations that need to synchronize their disparate mini functions within the organization into a single, integrated and functional one to enhance their environmental and air quality performance. Although it is a self-regulatory instrument, ISO standards are able to pull-in or work in combination with other instruments in their application. An example to this is the ISO 14001:2015 environmental management system (EMS) standard clauses 4.2 and 6.1.3. Clause 4.2 deals with understanding the needs and expectations of interested parties where all the relevant stakeholders (which include the civil society) must be identified as well as their relevant (environmental) needs which is primarily a civil-based approach. Clause 6.1.3 requires the organization to determine and have access to the compliance obligations related to its environmental aspects as well as taking them into account when implementing and improving the EMS system. This compliance obligations clause is primarily relating to the command-and-control instruments.

Other agreement-based instruments include the carbon disclosure project (CDP) which is a global initiative where the Johannesburg Stock Exchange (JSE)'s top 100 companies provide information on their carbon intensity with plans to reduce these. In this regard, companies are starting to request emissions data from their suppliers as they start to realize the pressures they can exert on suppliers in terms of their sphere of influence. The CDP for South Africa was released on 22 November 2007 in which the level of disclosure on most issues showed valuable improvement since 2009. Subsequently, 94% of responding companies disclosed their GHG emissions showing that there is a growing awareness of the risks and opportunities of climate change, although often at a general level. Also, there has been a notable increase in the number of companies voluntarily setting (or publicly committing to set) reduction targets. More companies are also implementing direct emissions reduction measures and encouraging signs of companies reducing emissions within their sphere of influence. In addition, as part of the CaC approach, the carbon tax act no. 15 of 2019 has obligatory requirements on the reporting of GHG emissions by organisations. Government is of the view that imposing a tax on greenhouse gas emissions and concomitant measures such as providing tax incentives for rewarding the efficient use of energy will provide appropriate price signals to help nudge the economy towards a more sustainable growth path.

Hybrid approach

Nel and Wessels (2010) argue that in all the governing instruments, there is not a single instrument that offers a one-size-fits-all solution to environmental challenges, meaning that every instrument has particular strengths and weaknesses when it comes to performance. Some of these instruments will have similar characteristics even though they belong to different categories of environmental management approaches. The

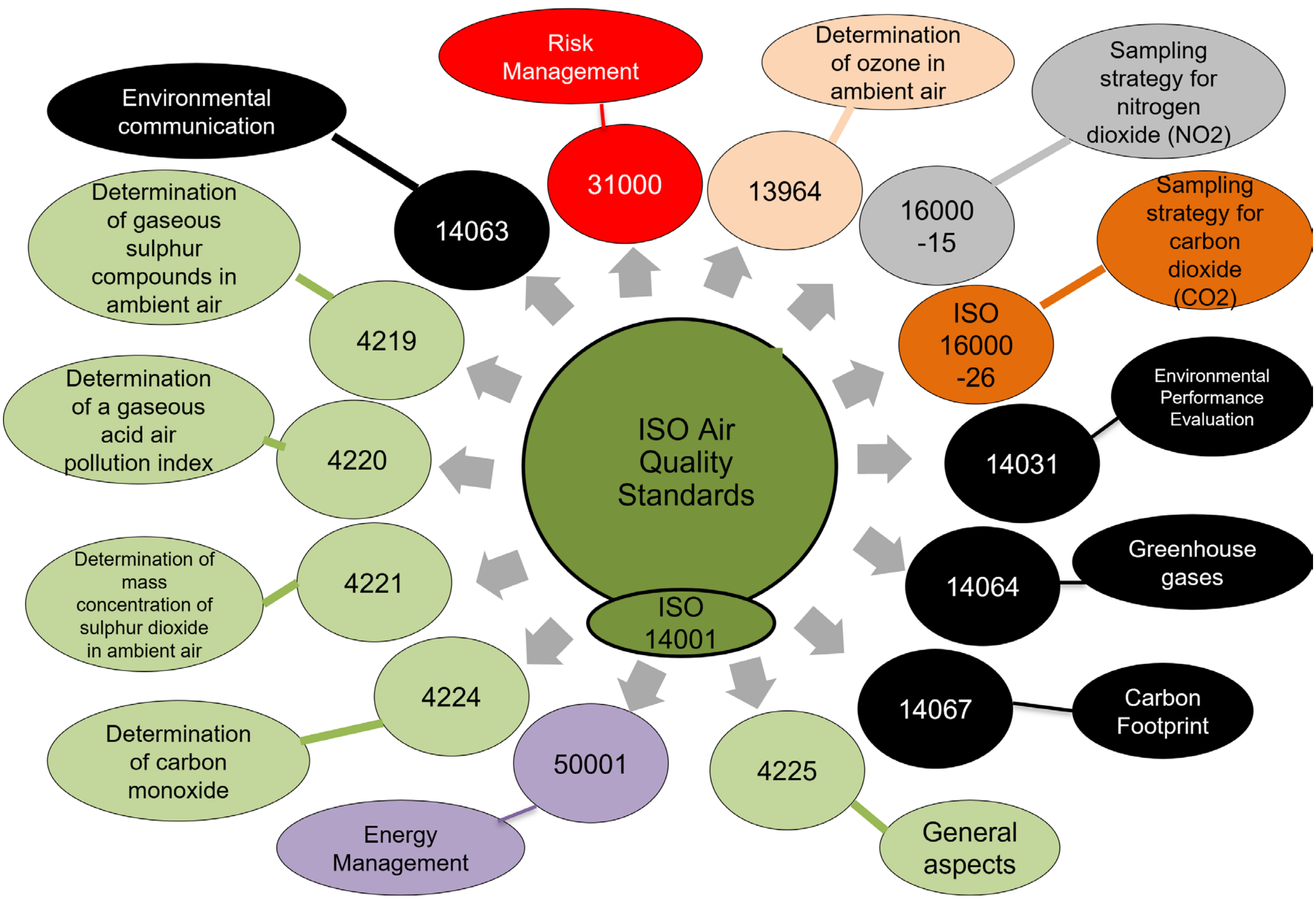


Figure 3: *International Organization for Standardization (ISO) standards relating to air quality.*

adoption of a hybridised approach, which is the integrated use of all the approaches to ensure sustainable governing efforts, is increasingly gaining popularity and organizations will adopt a combination of one or more instruments to address specific environmental issues (Nel and Alberts 2018). Internationally the application of more than one approach as part of a suite of instruments to address air quality challenges is recommended for effective air quality management. This is referred to as the "redundancy effect". This redundancy effect argues that multiple instruments provide a better chance of success while also providing checks and balances by allowing some instruments to either rectify the problem or to generate alternative solutions should one of them fail (Landau 1969, Taylor 1984, Nel and du Plessis 2001, Kirschke and Newig 2017, Nel and Alberts, 2018). This has been shown internationally where Paris, Sao Paulo, Mexico City and New York managed to address their vehicular emissions by using CaC based regulatory approaches focusing on circulation restriction, fuel and technology initiatives as well as fiscal incentive approaches in targeting fuel and technology initiatives (Slovic and Ribeiro 2018; Molina et al. 2019). The adoption and use of these instruments in a hybridised manner is also often specified as conditions in environmental authorisations (Nel and du Plessis, 2001; Nel and Wessels, 2010). Furthermore, another key aspect in adopting and using any suite of instruments is selecting them carefully to optimise synergy and avoid instruments working against each other, as well as to prevent injudicious and fruitless expenditure (Nel an Alberts, 2018). It is thus important to state that, separating these different approaches into classes is artificial or not really realistic in practice because most, if not all, instruments are hybridised in their application.

As shown in figure 4, there are four hybrid combinations that relate to the environmental management approaches discussed above. These approaches are: A=Fiscal/CaC Hybrid; B=Fiscal/Civil Hybrid; C=Civil/CaC Hybrid and D=Fiscal/Civil/CaC/Agreement Hybrid.

Examples relating to Fiscal/CaC hybrid (letter A in figure 4) include environmental levies such as carbon tax. Electric filament lamps, electricity generation, motor vehicle CO_2 emission, plastic bags, and tyres based on NEMA's "polluter pays principle" are other

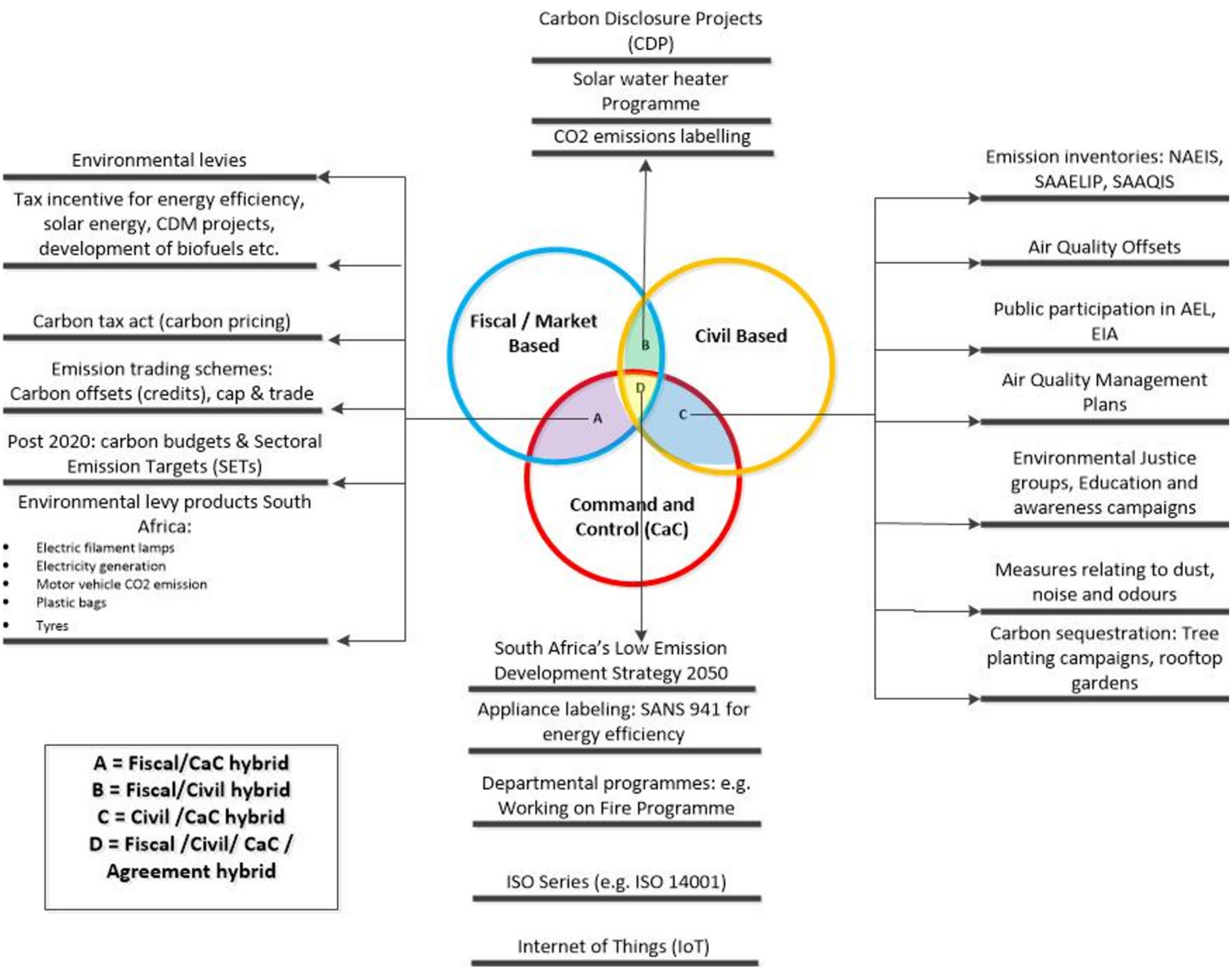


Figure 4: *Hybrid air quality governance and management instruments relating to: A=Fiscal/CaC hybrid; B=Fiscal/Civil Hybrid; C=Civil/CaC Hybrid and D=Fiscal/Civil/CaC/Agreement Hybrid.*

instruments which are imposed by the South African Customs and Excise Act, No. 91 of 1964 and administered by South African Revenue Services (SARS) in order to protect the environment by imposing tax on the CO_2 equivalent of greenhouse gas emissions (SARS, 2022).

The letter B in figure 4 provides for Fiscal/Civil Hybrid instruments which include instruments such as the solar water heater (SWH) programme. This programme was identified in the South African National Energy Efficiency Strategy of 2005 as integral to improving energy utilisation in South Africa with the aim to promote of broader socio-economic benefits for South Africans including the promotion and development of local manufacturing and the associated implementation of local content requirements, the promotion of small and medium enterprises, job creation and access to hot water for residential dwellings (Civil and Fiscal based instruments).

Instruments relating to the Civil/CaC Hybrid include emission inventories (i.e. SAAQIS, SAAELIP and NAEIS), air quality offsets, air quality management plans, measures relating to dust, noise and odours, as shown in figure 4 letter C. A recent example of this specific hybrid approach is the court case judgement handed in on 18 March 2022 between GroundWork and the Vukani Environmental Justice Movement versus the government on the air pollution challenges in the Highveld Priority Area (HPA). In this regard, the court ruled that government needs to pass regulations to implement and enforce the Highveld Priority Area AQMP which is aimed at cleaning up the air on the Highveld to meet health-based air quality standards (CER, 2022). Another popular instrument in this category is the role of public participation in EIA/AEL application processes. Public participation is mandatory in the application, scoping, and impact assessment phases of EIA/AEL and is considered as an important input to the EIA process to allow stakeholders to participate in environmental decision making (Sandham et al. 2019).

Instruments relating to the Fiscal/Civil/CaC hybrid approach as shown by letter D on figure 4 include Low-Emission Development Strategy (SA LEDS) 2050. This strategy describes how various sectors of the economy would implement policies and measures to reduce emissions up to 2050 as well as how it will ensure broader socio-economic development (DFFE 2018).

Other examples in this category include the working on fire programme which is a multi-partner programme that is mandated under the National Veld & Forest Fire Act of 1998 (CaC). This government-funded, job-creation programme is implemented by the FFA Group of Companies which is a leading supplier of Integrated Fire Management (IFM) services that takes up the youth from disadvantaged communities, trains them in fire awareness and education, prevention and fire suppression skills and employs them as participants (Civil-based). The creation of employment to participants provides an incentive for the participants to be economically active citizens (Fiscal-based instrument).

Another instrument in this category is the introduction of mandatory energy efficient labelling (SANS 941) for domestic appliances by African Bureau of Standards (SABS) (CaC based) in a bid to influence consumers purchase decisions (Civil based) to promote energy savings (Issock et al. 2018). The South African Energy Efficiency Label must be attached to all appliances that meet the minimum energy performance standards (MEPS) so that consumers have a choice when buying appliances (Fiscal-based). The label would include information on the energy consumption level of appliances. Examples of appliance programmes would include air conditioners, washing machines, electric ovens, refrigerators, electric geysers, audio and video equipment, dishwashers and electric lamps.

Discussion and conclusions

Government, civil society and the private sector have been developing, adopting, and implementing various air quality management instruments as a means to address and mitigate air quality management challenges in South Africa since the 1960s. Over recent years there has been a proliferation of instruments. However, no holistic conceptualised understanding of these instruments exists to critically inform air quality governance. The aim of this paper was to identify existing air quality management instruments and conceptualise them in terms of broader environmental management approaches (Nel and Alberts 2018). This allows for a critical understanding of the overall air quality governance framework in South Africa. The research results highlight the following main conclusions:

- *Over reliance on CaC*: The majority of instruments identified could be classified as CaC based. This means that policy and legislation essentially drive AQ management and governance, with a strong reliance on effective compliance and enforcement measures. Moreover, over reliance on CaC suggest limited innovation and incentive-based thinking. In light of the important role CaC instruments play the continual development and refinement thereof does however contribute positively to the overall governance framework such as the review of the national ambient air quality standards, priority areas regulations and the SAAELIP data policy (DFFE 2021). Therefore, although the important role of CaC approaches is acknowledged, further expansion of approaches beyond CaC is recommended.
- *Lack of innovative hybridisation across approaches*: The research results show a high level of hybridisation, especially in relation to CaC. This again suggests that, even where fiscal and civil based thinking is applied, it tends to rely on CaC arrangements. For example, financial incentives are still based in law and the mandate for civil society to effect change is ultimately reliant on access to the courts. We still seem to be far away from real innovative thinking around incentive and community-based solutions to air quality management.
- *High level of complexity*: Dealing with air pollution and air quality management is fundamentally complex especially in the South African context. This is partially as a result of the maturity and complexity of the South African air quality

management legal framework (Nel and Alberts, 2018). As a result of this complexity, many of the most effective management instruments do not fit neatly into a specific approach, but rather are designed as hybrid instruments. There clearly exists a need to deal with this complexity by finding ways to simplify the legal framework and find a more balanced approach with less reliance on enforcement and more reliance on incentives. This research is therefore in agreement with earlier studies that the solution to air pollution lies in a holistic and balanced approach (Nel and du Plessis 2001, W. 2001, Engelbrecht and van der Walt 2007).

- *Lack of synergy*: This study suggests that there is often lack of synergy among the instruments in their application. These instruments often have different objectives addressing specific issues at different levels from strategic, tactical, and political, operational and technical instruments. An understanding of the level of application of each instrument is therefore important to yield an effective adoption and implementation (Nel and Alberts, 2018). For example, specific legal requirements around energy generation are often a disincentive to innovation and/or the use of new technologies. This is because, based on the current legal requirements, it is challenging for the individual power producers to generate and make this power accessible to the market, particularly to those entities intending to sell further, such as municipalities. Therefore, CaC based instruments should aim to provide a regulatory framework that invites incentives and innovation towards dealing with environmental challenges. The current over reliance on compliance and enforcement with limited discretion built into the licencing processes suggests failure in this regard.

Finally, the research notes that even amidst the plethora of instruments, some of which have been in existence for decades, such as AQMPs and AELs, South Africa is still facing serious air quality challenges especially in those areas that have been declared as priority areas (September 2012; Tshehla, and Wright 2019). This raises the very important question as to how effective different instruments are in achieving their goals and how effective the overall air quality management system is in dealing with air quality challenges. We hope that the conceptualisation provided in this paper provides a basis and first step towards a more detailed analysis of the strengths, weaknesses, and performance of different approaches and instrument to ensure effective air quality governance and management in South Africa.

Note

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Appendix A

Appendix A shows other pieces of national legislations directly or indirectly linked to the management of air quality as adopted and updated from the 2017 National Framework for Air Quality Management in the Republic of South Africa.

***Table 1:** Command and control instruments for air quality management with relevant examples.*

Legislation	Air quality management links	Relevance
Climate Change Bill	• Transitional provisions relating to the Declaration of greenhouse Gases as Priority Air Pollutants, the National Pollution Prevention Plans Regulations and the National Greenhouse Gas Emissions Reporting Regulations published in terms of the National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004)	To enable the development of an effective climate change response and a long-term, just transition to a low-carbon and climate-resilient economy and society for South Africa in the context of sustainable development
National Building Regulations and Building Standards Act 103 of 1977	• To further efforts to decrease energy consumption and associated GHG emissions of new commercial and residential buildings, the government has implemented energy efficiency and energy consumption standards under the National • Building Regulations and Buildings Standards Act. The first of these is South African National Standard (SANS) 204 ± Energy Efficiency in Buildings. This standard [3]specifies the design requirements for energy efficiency in buildings and of services in buildings with natural environmental control and artificial ventilation or air conditioning systems. ´ The second, SANS 10400-XA ± Energy Usage in Buildings, includes the provisions of SANS 204 and others, providing a standard for energy efficient buildings	To provide for the promotion of uniformity in the law relating to the erection of buildings in the areas of jurisdiction of local authorities; for the prescribing of building standards
Carbon Tax Act (Act No. 15 of 2019)	• Gives effect to the “polluter pays” principle of NEMA • Price carbon by internalizing the costs of emitting carbon	To provide for the imposition of a tax on the carbon dioxide (CO_2) equivalent of greenhouse gas emissions; and to provide for matters connected therewith
National Key Points Act, 1980 (Act No. 102 of 1980)	• Provides for the protection of significant State or private assets, relative to national security • Regulates the flow of information regarding Key Point activity • Allows for measures to be implemented to maintain the security of a Key Point	Many significant emitters have been classified as National Key Points, and the Act is used to regulate access to information
Protection of information Act, 1982 (Act No. 84 of 1982)	• Covers the protection of information related to defence, terrorism and hostile organisations • Information regarding these activities in any form is prohibited access and cannot be disseminated • Prohibited places can be declared, which also fall under this protection	Can be used to regulate access to information on air quality
Conservation of Agricultural Resources Act, 1983 (Act No. 43 of 1983)	• Regulates burning of veld, except in state forests • Allows for control and prevention of veld fires through prescribed control measures • Allows for control measures to be prescribed regarding the utilisation and protection of veld that has been burned	Addresses controlled burning, which directly impacts on ambient air quality
Local Government Municipal Structures Act, 1988 (Act No. 117 of 1998)	• Establishes municipal categories • Designates functions and powers of municipalities	Specifies that responsibility for integrated development planning, within which air quality management plans must reside, rests with district municipalities
National Veld and Forest Fires Act, 1988 (Act No. 101 of 1998)	• Purpose is to combat and prevent veld, forest and mountain fires • Fire Protection Agency can be designated for control and has power to conduct controlled burning with respect to conservation of ecosystems and reduction of fire danger • Lighting, maintenance and using of fires is regulated	Addresses controlled burning, which directly impacts on ambient air quality

Legislation	Air quality management links	Relevance
National Water Act, 1998 (Act No. 36 of 1998)	• Establishes strategy to address management of water resources including protection and use of water • Establishes management agencies • Provides for pollution prevention and remediation, including land-based sources • Addresses emergency incidents, including land-based pollutant sources	Pollution sources from land-based activities that impact on water resources
Local Government Municipal Systems Act, 2000 (Act No. 32 of 2000)	• Provides a framework for planning by local government • Describes contents of an integrated development plan and the process to be followed	Air quality management plans are to be incorporated into integrated development plans
Occupational Health and Safety Act, 1993 (Act No. 85 of 1993)	• Provides for the health and safety of persons at work, including atmospheric emission from workplaces • Sets out certain general duties of employers and to their employees • Empowers the Minister of Labour to make regulations regarding various matters • Further require any employer to ensure that their activities do not expose non-employees to health hazards	The air emissions from the workplace environment has atmospheric quality implications
Promotion of Access to Information Act, 2000 (Act No. 2 of 2000)	• Facilitates constitutional right of access to any information whether held by State or another person (if it is related to exercise or protection of a right) • Details the means to access records, whether public or private • Does not detract from provisions in the NEMA Section 1 and Section 2 • Allows for denial of access based on defence, security or international relations	Promotes access to information, including air quality information, although it has provisions for refusing access
Promotion of Administrative Justice Act, 2000 (Act No. 3 of 2000)	• Details the administrative procedure to be followed when carrying out an administrative action, and the process of review	Formal interactions between government departments, the public and other stakeholders by informing due process in decision-making
International Trade Administration Act, 2002 (Act No. 71 of 2002)	• Establishes the International Trade Administration Commission as an administrative body • Regulates the import and export of controlled substances	Import and export control related to ozone-depleting substances through the declaration of controlled substance
Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002)	• States that environmental authorisation is required for obtaining prospecting and mining right • For environmental authorisations, scoping, EIA, specialist reports (including air quality specialist report), and EMP are needed. The Act states that it is necessary to submit an environmental management programme if applying for a mining right, and an environmental management plan if applying for reconnaissance permission • The Minister is required to consult with any state department which administers any law relating to matters that affect the environment and must request the comments of that department on the environmental plan or programme being considered • Provisions are made for monitoring and auditing of environmental performance • Regulation 64 of MPRDA regulations stipulates that, the holder of a mining right or permit must comply with laws relating to air quality management and control • Stockpiles require compliance monitoring and decommissioning • Closure certificate authorisation is dependent on approval from other environmental departments that potential environmental impacts have been addressed	Grants the decision-making power on matters potentially affecting the air environment to the Minister of Minerals and Energy in the case of mining activities but includes the obligation to comply with the AQA

Legislation	Air quality management links	Relevance
National Health Act, 2003 (Act No. 61 of 2003)	• Makes reference to the performing of environmental pollution control by municipalities. • Municipal health services are defined as including the responsibility for environmental pollution control • The responsibility for municipal health services rests with metropolitan and district municipalities • National and provincial departments of health have the duty to perform environmental pollution control	Air quality management falls within environmental pollution control
Intergovernmental Relations Framework Act, 2005 (Act No. 13 of 2005)	• Determines a framework to facilitate interaction and co-ordination, in the implementation of legislation, between spheres of government • Principles of participation, consultation and consideration are included • Establishes structures for coordination at different spheres of government • Establishes an implementation protocol mechanism as a tool for coordination • Provides mechanisms for conflict resolution, including the appointment of a facilitator	Provides mechanisms for coordination and conflict resolution across spheres of government in aspects of legislative implementation
National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008)	• Promotes cleaner technology, cleaner production and consumption practices for pollution minimisation • Addresses impacts of waste disposal on the environment, including air • Provides for numerous measures related to waste disposal including standards, integrated waste management planning, municipal waste management, priority wastes, licensing, waste management information system	Closely linked through issues of emissions to the air from thermal treatment activities and landfill sites
Disaster Management Act, 2002 (Act No. 57 of 2002)	• Provides for the declaration of certain areas as disaster areas; • Disaster is defined as including the damage to the environment; • Provides for an integrated and co-ordinated disaster management policy that focuses on preventing or reducing the risk of disasters, mitigating the severity of disasters, emergency preparedness, rapid and effective response to disasters and post-disaster recovery; • Provides for the establishment of national, provincial and municipal disaster management centres	Certain air pollution episodes can be disastrous. Inversely, certain disasters result in air pollution
Accreditation for Conformity Assessment, Calibration and Good Laboratory Practice, 2006 (Act No. 19 of 2006)	• Provides national and international recognition of the reliability of data produced by conformity assessment bodies involved in air quality management	An accreditation service can be used to provide confidence to stakeholders regarding the reliability of data produced by conformity assessment bodies


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Research article

Temperature modifies the association between air pollution and respiratory disease hospital admissions in an industrial area of South Africa: The Vaal Triangle Air Pollution Priority Area

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Abstract

Background: Epidemiological studies reported independent effects of air pollution and temperature on health, yet these two exposures are often treated as separate risk factors. Few studies investigated temperature effect modification on the health effects of air pollution in Africa and none examined the effects of black carbon on respiratory disease (RD) hospitalisations. The aim of this study was to determine whether the association between RD hospitalisations and air pollution in the Vaal Triangle Air Pollution Priority Area was modified by apparent temperature (Tapp) during January 2013 to February 2020.

Methods: RD admission data (ICD10 J00-J99) were obtained from two hospitals located in Vanderbijlpark and Vereeniging. Ambient PM_{10}, $PM_{2.5}$, BC, NO_2, SO_2 and O_3, temperature and relative humidity data were obtained from six monitoring stations. A case-crossover epidemiological study design was applied. Lag0-1 was investigated, i.e. the average air pollutant level on the day and the day before hospitalisation. Models were adjusted for public holidays and Tapp. Effect modification was investigated by stratifying days into low, moderate and high Tapp days. Susceptibility by age and sex was investigated.

Results: Of the 43 386 hospital admissions, 50.9% (n=22 092) were women and 51.4% (n=22 304) were 0-14-year olds. Air pollutants exceeded the daily WHO air quality guidelines generally on more than 50% of the days. In general, moderate Tapp worsened the effects of $PM_{2.5}$, PM_{10}, SO_2 and BC, whilst the effects of NO_2 and O_3 were most pronounced on days with high Tapp. The elderly and females were more vulnerable to air pollution, especially on days with moderate Tapp.

Conclusions: These results indicate that the risk of RD hospitalisation due to ambient air pollution exposure is different on low, moderate and high Tapp days in Vanderbijlpark and Vereeniging.

Keywords

Air pollution, PM_{10}, $PM_{2.5}$, NO_2, SO_2, O_3, black carbon, apparent temperature; respiratory disease; hospital admissions; South Africa; heat effects; case-crossover

Introduction

The World Health Organization (WHO) concluded that the burden of disease attributable to air pollution is on a par with other major global health risks such as tobacco smoking and unhealthy diet (WHO, 2021). Therefore, air pollution is now acknowledged as the single biggest environmental threat to human health. The Global Burden of Disease Study estimated that air pollution was the reason for 1.1 million deaths across Africa in 2019 (GBD 2019 Risk Factor Collaborators, 2020). It is estimated that the majority of these deaths occur in low– and middle–income countries (LMIC), however these estimates are based mostly on exposure-response functions derived from epidemiology studies conducted in developed countries (Cohen et al., 2017; Ostro et al, 2018; WHO, 2021). More air pollution epidemiological studies need to be conducted in LMIC, such as South Africa (Ostro et al. 2018).

Ambient temperature is another major environmental risk factor of human health (Romanello et al., 2022). Climate change is projected to have dangerous effects on weather patterns and temperature globally in the near future (Romanello et al., 2022). Both heat and cold exposure are risk factors for human health, but most studies focused on heat (Ryti et al., 2016; Song et al., 2017; Vicedo-Cabrera et al., 2018). Epidemiological studies in Africa and other LMIC on the human health effects of heat and cold are lacking (Amegah et al., 2016; Wichmann, 2017; Green et al., 2019). LMIC populations are more susceptible to temperature extremes due to inadequate infrastructure, healthcare services, technology (Green et al., 2019). It is projected that by 2080, temperature increases greater than 4°C will be observed across South Africa (Department of Environment, Forestry and Fisheries, 2020).

Most air pollution epidemiological studies adjust for ambient temperature as a confounder in regression models (Atkinson et al., 2014; 2015; Chen et al., 2017; Li et al., 2017; Abed et al., 2020; Orellano et al., 2020; Grigorieva, & Lukyanets, 2021; Areal et al., 2022). During the last decade research emerged on whether the effects of air pollution on human health are modified by temperature (Chen et al., 2017; Li et al., 2017). Most of these studies focused on cause-specific mortality, such as respiratory, cerebrovascular diseases and specific cardiovascular diseases. Fewer studies globally investigated cause-specific hospital admissions (Abed Al Ahad et al., 2020; Lokotola et al., 2020; Olutola and Wichmann, 2021; Areal et al., 2022). The evidence so far is ambiguous and studies are lacking in LMIC. The WHO recommended more epidemiological studies that investigate temperature effect modification of air pollution along with more studies that focus on BC, NO_2 and SO_2 exposure (WHO, 2021).

To address the gaps in understanding the human health effects due to the interaction between ambient air pollution and temperature exposure, this study investigated respiratory disease hospital admissions during a study period of just over seven years in one of the most polluted areas in South Africa, namely the Vaal Triangle Air Pollution Priority Area (VTAPA). Susceptibility by sex and age groups (0–14, 15–64 years and ≥65 years) was also investigated.

Material and methods

Study area

Vereeniging and Vanderbijlpark are located in the VTAPA (Figure 1). The two cities border each other directly. Air pollution priority areas are air pollution hot spot areas of concentrated industrial activities (Naiker et al., 2012).These air pollution hot spot areas are declared as priority areas according to the National Environmental Management: Air Quality Act, 2004, i.e. if the Minister of Environmental Affairs or Member of the Executive Committee reasonably believes that: ambient air quality standards are being, or may be, exceeded in the area, or any other situation exists which is causing, or may cause, a significant negative impact on air quality in the area; and the area requires specific air quality management action to rectify the situation (Department of Environmental Affairs 2005). Three National Priority Areas have so far been declared: The VTAPA, the Highveld and the Waterberg-Bojanala Priority areas in 2006, 2007 and 2012, respectively.

Study design

The associations between air pollution and respiratory disease hospital admissions were investigated with the case-crossover epidemiological design, as done in numerous other studies globally (Chen et al., 2017; Li et al., 2017; Song et al., 2017) and in South Africa (Lokotola, Wright and Wichmann, 2020; Olutola and Wichmann, 2021; Thabethe, Voyi & Wichmann 2021; Wichmann & Voyi 2012, Shirinde and Wichmann, 2022).

The case-crossover epidemiological study design was developed as a variant of the case-control epidemiological design to study the effects of transient exposures on emergency events, comparing each person's exposure in a time period just prior to a case-defining event with each person's exposure at other times (Maclure, 1991). If the control days are chosen close to the event day, personal characteristics that vary slowly over a short time period of 24 hours are controlled by matching. Such characteristics may include co-morbidities (e.g. HIV status, hypertension, smoking status and so forth). Nevertheless, such characteristics may be potential effect modifiers, i.e. indicate susceptibility. However, information on such characteristics is not provided by hospital registers.

The time-stratified approach was applied to select the control days, defining the day of hospital admission as the case day and the same day of the week in the same month and year as control days (i.e. theoretically 3 to 4 control days per case day) (Carracedo-Martínez et al., 2010). The incidence of hospital admissions is likely to be influenced by time-varying factors, such as day of the week, public holidays, long-term trend and seasonality. In case-crossover study design, day of the week, long-term trend and seasonality are controlled by design.

Hospital admission data

Respiratory disease hospital admission data (International Classification of Disease, 10th version [ICD-10] (J00–J99) were obtained from two hospitals located in Vereeniging and Vanderbijlpark after ethical approval had been obtained (Reference 132/2018 and 433/2021, Research Ethics Committee, Faculty of Health Sciences, University of Pretoria) (Figure 1). Data from the two hospitals were available electronically from 1 January 2013 – 29 February 2020.

Air pollution and weather data

$PM_{2.5}$, PM_{10}, BC, NO_2, SO_2 and ground-level O_3 were investigated for the study period 1 January 2013 to 29 February 2020 and downloaded as daily averages from the SAAQIS website. The South African Weather Services (SAWS) manages the data that are deposited in the South African Air Quality Information System. The air pollution data source is the same as the very large study of 682 cities (Liu et al., 2019) and other local studies (Adebayo-Ojo et al., 2022; Olutola and Wichmann, 2021, Shirinde and Wichmann, 2022). A network of six air pollution monitors were assigned to the VTAPA (South African Air Quality Information System 2022) and these continuously assess real-time concentrations of the criteria air pollutants using equivalent methods of the United States Environmental Protection

Agency and in accordance with ISO 17025 guidelines (National Environmental Management: Air Quality Act, 2004) (Figure 1). This Act requires the monitoring of criteria air pollutants.

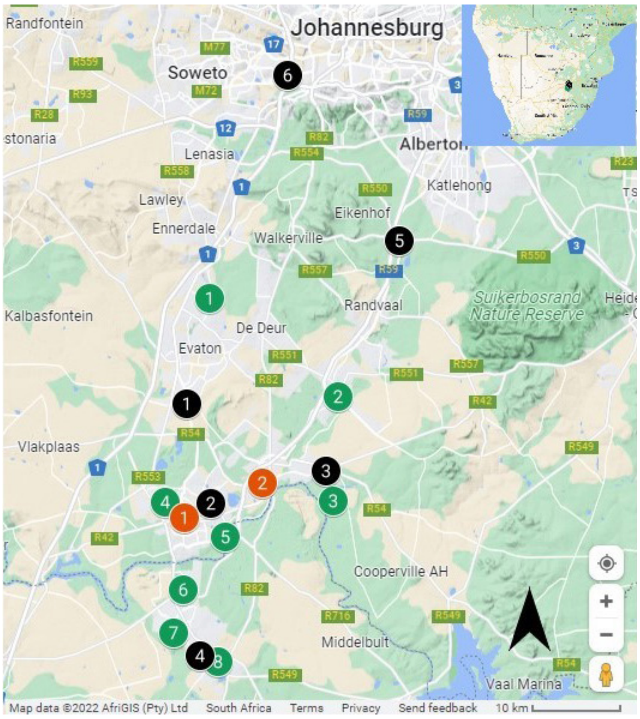

Figure 1: Map of the location of the air pollution stations in the Vaal Triangle Air Pollution Priority Area and the two hospitals
Red symbols are the hospitals (1) Vanderbijlpark and (2) Vereeniging.
Black symbols are the pollution monitoring stations of the VTAPA: (1) Sebokeng, (2) Sharpeville, (3) Three Rivers, (4) Zamdela, (5) Kliprivier, (6) Diepkloof.
Green symbols are the pollution monitoring stations of the City of Johannesburg:(1) Orange Farm, (2) Meyerton, (3) Randwater, (4) Vanderbijlpark, (5) North West University, (6) Bongani Mabaso Eco Park, (7) AJ Jacobs, (8) Leitrim.

Data of all six air pollution monitoring stations of the VTAPA (Kliprivier, Diepkloof, Zamdela, Sebokeng, Sharpeville and Three Rivers) were applied in the study as people are mobile and are not just based all the time in the area where the two hospitals are located. In addition, measurements are also collected by the six stations for meteorological data such as wind speed, wind direction, ambient temperature, relative humidity and rainfall. This study applied applied temperature and relative humidity to calculate apparent temperature (Tapp).

In order to minimise exposure misclassification, eight other air pollution monitoring stations in the vicinity of the VTAPA, managed by City of Johannesburg (see Figure 1), were also considered. However, these stations had missing data for several years and the data were not applied in this study.

This study investigated Tapp, which reflects the physiological experience of combined exposure to humidity and temperature and thereby better capture the response on health than temperature alone (Steadman, 1984). Song et al 2017 in a recent review stated that Tapp is considered to be a better temperature exposure metric than temperature, especially for the effects of heat exposure on morbidity or mortality.

The following equations were used to calculate the Tapp (Steadman 1984)

$$\text{Saturation vapour pressure} = 6.112 \times 10^{(7.5 \times \text{temperature °C}/ (237.7 + \text{temperature °C})} \quad (1)$$

$$\text{Actual vapour pressure} = (\text{relative humidity (\%)} \times \text{saturation vapour pressure})/100 \quad (2)$$

$$\text{Dew point temperature °C} = (-430.22 + 237.7 \times \ln(\text{actual vapour pressure}))/-\ln(\text{actual vapour pressure}) + 19.08) \quad (3)$$

$$\text{Apparent temperature °C} = -2.653 + (0.994 \times \text{temperature °C}) + 0.0153 \times (\text{dew point temperature °C}) \quad (4)$$

Statistical analysis

Missing air pollution and meteorological data were imputed with the missing data imputation by chain equations (MICE) method, which is commonly applied in air quality studies (Gómez-Carracedo et al., 2014; Hadeed et al., 2020; Hajmohammadi & Heydecker 2021; Van Buuren & Groothuis-Oudshoorn, 2011).

The data were assumed to be missing at random. This means the missing data being observed within a variable is independent of the value of itself, however, it is dependent on other variables which are included in the data set (Allison, 2009). According to the monthly SAAQIS reports some of the reasons for missing data were power failures, station vandalism and faulty instruments (SAAQIS, 2020). MICE is a particular multiple imputation method that can only be used under the missing at random assumption of missing data (Azur et al., 2011).

The 'mice' package in the R statistical programme was applied. The mice predictive mean algorithm imputation option was used, which draws imputations from the observed data, imputed values had the same gaps as in the original data, and were always within the range of the original dataset (Karahalios et al., 2012). This method ensures that no imputations are outside the original data range, which produces more reliable results (Chinomona and Mwambi, 2015). Each air pollutant was imputed individually from each of the six air monitoring stations. Pollution data from one station was used to impute each pollutant. Thereafter overall averages for the VTAPA area were calculated for each pollutant.

The correlations between the air pollutants and Tapp were investigated using Spearman rank correlation analyses. As in other studies on temperature or Tapp as a modifier, the results in the present study focused on lag0-1. i.e. mean of lag0 (same day of exposure as day of hospitalisation) and lag 1 (day prior to day of hospitalisation) (Chen et al., 2017; Li et al., 2017, Song et al., 2017, Lokotola et al., 2020; Olutola and Wichmann, 2021;

Thabethe et al. 2021; Shirinde and Wichmann, 2022; Adebayo-Ojo et al., 2022).

Daily and yearly air pollution levels were compared to the daily and yearly WHO air quality guidelines (WHO, 2021) and South African air quality standards (National Environmental Management: Air Quality Act, 2004).

Stratified analyses were used to investigate the modification effects of lag0-1 of Tapp. High and low Tapp days were defined as days when Tapp was higher than the 75th percentile level in the study period (19.5°C) and lower than the 25th percentile level (11.7°C), respectively. Moderate Tapp days were those equal or higher than the 25th percentile level, but lower or equal to the 75th percentile level. A similar approach was followed in other studies (Chen et al. 2017; Li et al. 2017, Lokotola et al. 2020; Olutola and Wichmann, 2021; Shirinde and Wichmann, 2022).

The association between the air pollutants and respiratory disease hospital admissions was investigated using conditional logistic regression models. Only single pollutant models were investigated as pollutants were all significantly correlated with each other ($p<0.05$). Models were adjusted for public holiday variable (binary variable) and Tapp.

The shape of the association between Tapp and respiratory disease hospital admissions was investigated. Tapp was included as a natural spline with 3 degrees of freedom (df) (non-linear term) in the models, as done in other studies (Wichmann et al. 2014, 2017, Lokotola et al. 2020; Olutola and Wichmann, 2021; Thabethe et al. 2021; Shirinde and Wichmann, 2022). Whether the non-linear term of Tapp improved the model was checked with log likelihood ratio tests, i.e. compared it to a model that included Tapp as a linear term. It was observed that the non-linear term of Tapp was not significantly associated with the hospital admissions and also did not add value to the model. Hence, Tapp was included as a linear term in the models. Air pollutants were added as linear terms in the model, as done in many studies (Chen et al. 2017; Li et al. 2017, Wichmann, 2017, Lokotola et al. 2020; Olutola and Wichmann, 2021; Thabethe et al. 2021; Shirinde and Wichmann, 2022; Adebayo-Ojo et al., 2022).

The associations were presented as the percent excess risk in hospital admissions per 10 $\mu g.m^{-3}$ increase in an air pollutant level, except for BC. The range of BC levels was small, hence an increase per 1 $\mu g.m^{-3}$ was applied. This approach is commonly applied in other studies (Chen et al. 2017; Li et al. 2017, Lokotola et al. 2020; Olutola and Wichmann, 2021; Shirinde and Wichmann, 2022).

Susceptibility by sex and age groups (0–14 years, 15–64 years and ≥65 years) on low, moderate and high Tapp days was also investigated.

Results and discussion

Descriptive statistics

Table 1 summarises the characteristics of the respiratory disease hospital admissions and Supplementary Figure 1 illustrates the time-series of the daily admissions. In total 43 386 admissions were included in the study and between 1 and 55 respiratory disease hospital admissions were recorded daily. Males and females had similar number of admissions, whilst more than half occurred amongst the youngest age group (0–14 years). Clear seasonal trends were observed with more admissions during the colder months (May to August) than during the warmer months (September to April) (Figure 1). The majority of respiratory disease hospital admissions occurred on moderate Tapp days (50%), followed by 31% and 19% on days with low and high Tapp, respectively.

Table 1: *Daily descriptive statistics of respiratory disease hospital admissions in Vereeniging and Vanderbijlpark, South Africa and air pollutants and weather conditions in the Vaal Triangle Air Pollution Priority Area, South Africa, 1 January 2013 – 29 February 2020 (2616 days).*

Variable	Mean	Min	P25	Median	P75	Max
Hospital admissions						
All ages and both sexes (n=43 386)	16.6	1	11	15	21	55
Females (n=22 092)	8.4	0	5	8	11	35
Males (n= 21 294)	8.1	0	5	7	11	30
0–14 year olds (n=22 304)	8.5	0	5	8	11	37
15–64 year olds (n=15 810)	6.0	0	4	6	8	27
≥65 year olds (n=5 272)	2.0	0	1	2	3	16
Exposure						
PM_{10} ($\mu g.m^{-3}$)	51.7	12.5	38.2	48.3	62.4	131.8
$PM_{2.5}$ ($\mu g.m^{-3}$)	30.4	7.3	22.7	28.5	36.0	80.6
Black carbon ($\mu g.m^{-3}$)	3.2	0.4	1.9	2.7	4.0	9.6
NO_2 ($\mu g.m^{-3}$)	30.7	8.0	23.4	28.9	36.0	80.8
SO_2 ($\mu g.m^{-3}$)	15.6	2.4	9.6	13.6	19.4	63.6
O_3 ($\mu g.m^{-3}$)	50.2	14.3	40.0	49.3	59.3	103.9
Tapp (°C)	15.6	-2.2	12.5	16.3	19.1	28.1
Temperature (°C)	17.1	0.4	14.0	17.7	20.5	29.8
Relative humidity (%)	49.9	13.1	40.7	50.3	59.6	85.1

Abbreviations: PM_{10}: particulate matter with an aerodynamic diameter equal or smaller than 10 µm; $PM_{2.5}$: particulate matter with an aerodynamic diameter equal or smaller than $_{2.5}$ µm; SO_2: sulphur dioxide; NO_2: nitrogen dioxide; O_3: ground-level ozone; Tapp: apparent temperature

Table 1 also summarises the descriptive statistics for daily air pollutant and Tapp levels, whilst Supplementary Figures 2 to 9 present the time-series of the exposure variables. The mean Tapp was 15.6°C and ranged between -2.2°C to 28.1°C.

The highest PM_{10}, $PM_{2.5}$, BC, NO_2, SO_2 and O_3 levels were 131.8 µg.m^{-3}, 80.6 µg.m^{-3}, 9.6 µg.m^{-3}, 80.8 µg.m^{-3}, 63.6 µg.m^{-3} and 103.9 µg.m^{-3}, respectively. The daily PM_{10}, $PM_{2.5}$ and SO_2 and NO_2 levels exceeded the daily WHO air quality guidelines of 45 µg.m^{-3}, 15 µg.m^{-3}, 40 µg.m^{-3} and 25 µg.m^{-3} on 1 532, 2 544, 47 and 1 771 days of the 2616 days, respectively (Figure 2) (World Health Organization, 2021). There is no daily WHO guideline for O_3. The more lenient South African daily air quality standards of 75 µg.m^{-3}, 40 µg.m^{-3} and 125 µg.m^{-3} were exceeded on 332, 452 and zero days, respectively for PM_{10}, $PM_{2.5}$ and SO_2 (National Environmental Management: Air Quality Act, 2004). There is no daily South African air quality standard for NO_2 or O_3.

Agbo et al (2021) reviewed 211 journal articles from air pollution exposure assessment studies that were conducted in 27 of the 54 African countries, including South Africa. These were published between 2006 and 2018. Outdoor PM_{10} daily levels ranged from 0.06 µg.m^{-3} in Rukomechi, Zimbabwe (Nyanganyura et al., 2007; Agbo et al., 2021) to 7154 µg.m^{-3} in Nouna, Burkina Faso (Yamamoto et al., 2014; Agbo et al., 2021). Daily and yearly mean PM_{10} levels exceeded the WHO guidelines for the majority of the 24 African cities that had available PM_{10} data. Thabethe et al. (2020) and Adebayo-Ojo et al. (2022) reported daily PM_{10} levels in three large South African cities that ranged from 6.9 to 121.5 µg.m^{-3} in Cape Town, 5.8 to 146.4 µg.m^{-3} in Durban and 7.7 to 273.3 µg.m^{-3} in Johannesburg during 2006–2016. Data for the three cities were obtained from the air quality monitoring networks of the municipalities. Outdoor PM_{10} daily levels at industrial areas across Africa ranged from 14.9 µg.m^{-3} at Sour El Ghozlane, Algeria (Khedidji et al., 2017; Agbo et al., 2021) to 1780.2 µg.m^{-3} in Illorin, Nigeria (Adeniran et al., 2017; Agbo et al., 2021). Daily PM_{10} levels ranged from 0 to 496.9 µg.m^{-3} during 2011-2016 in the Highveld Airshed Priority Area, a heavily industrialised region in the Mpumalanga province, South Africa (Olutola & Wichmann, 2021). A large study reported a yearly mean PM_{10} level (56 µg.m^{-3}) in 24 countries worldwide, whilst the lowest mean was observed in Sweden (14 µg.m^{-3}) and the highest in China (89 µg.m^{-3}) (Liu et al., 2019). The only country from Africa that was included in this large global study was South Africa with a mean of 59 µg.m^{-3}.

The range of daily $PM_{2.5}$ levels in the VTAPA during 1 January 2013 – 29 February 2020 was higher than those recorded by the South African government at 21 ambient air quality monitoring stations in 5 provinces in 2012 (4.9 to 43.3 µg.m^{-3}) (Altieri and Keen (2019). $PM_{2.5}$ levels were also lower during April 2017 to April 2018 in Cape Town, a large coastal city in the country, and Thohoyandou, a rural non-industrial town in the north of the country (Novela et al., 2020; Williams et al., 2021). $PM_{2.5}$ levels were lower in Pretoria, the administrative capital of South Africa during April 2017 to February 2020 (Adeyemi et al., 2022; Howlett-Downing et al., 2022). Outdoor $PM_{2.5}$ daily levels ranged from 0 to 535 µg.m^{-3} in Jinja and Kampala, Uganda (Kirenga et al., 2015). Daily $PM_{2.5}$ data were available for 22 cities across Africa and exceeded the corresponding WHO guideline (15 µg.m^{-3}) in nearly all towns (Agbo et al 2021). Lower $PM_{2.5}$ levels were reported during July 2015 to June 2016 in the Greater Tubatse Municipality, Limpopo province, South Africa. Three ferrochrome smelters and over fifteen operational chromium, platinum and silica mines are located in this municipality (Tshehla and Djolov, 2018). A similar $PM_{2.5}$ mean level (32 µg.m^{-3}) was reported during January 2011 to October 2016 in the Highveld Airshed Priority Area, a heavily industrialised region in the Mpumalanga province, South Africa, (Olutola and Wichmann, 2021). Daily mean $PM_{2.5}$ levels in industrial locations ranged from 8.2 to 384 µg.m^{-3} in Kampala (Kirenga et al., 2015). The yearly mean level in 16 countries worldwide was 35.6 µg.m^{-3}, whilst the lowest mean was observed in Australia (7 µg.m^{-3}) and the highest in China (52 µg.m^{-3}) (Liu et al., 2019). The study reported a mean of 31 µg.m^{-3} for South Africa.

There is a lack of studies in Africa that reported on BC levels and their health effects. The mean BC level (1.28 µg.m^{-3}) in Thohoyandou was lower (Novela et al. 2020). A study from Nairobi, Kenya reported a higher mean of 2.7 µg.m^{-3} for BC (Gaita et al. 2014). A study estimated BC levels in Africa and reported the lowest level in South Africa (2.1 µg.m^{-3}) and the highest level in Benin (16 µg.m^{-3}) (Bachwenkizi et al. 2021). A study from London, UK reported a lower mean BC level (1.5 µg.m^{-3}) during 2011–2012 (Samoli et al., 2016), whilst a study from the Uzice region, Serbia observed a higher mean BC level (33.9 µg.m^{-3}) during 2012–2014 (Tomic-Spiric et al., 2019).

Daily NO_2 levels in three large South African cities ranged from 3.4 to 59.8 µg.m^{-3} in Cape Town, 9.9 to 131.1 µg.m^{-3} in Durban and 0.9 to 123.1 µg.m^{-3} in Johannesburg during 2006–2016 (Thabethe et al. 2020; Adebayo-Ojo et al., 2022). In the review by Agbo et al (2021), data on NO_2 were available for 14 countries from 26 studies and indicated that traffic and industrial activities impacts NO_2 levels. Yearly mean levels of outdoor NO_2 ranged between 0.6 µg.m^{-3} in Okaukuejo, Namibia (Martins et al., 2007) and 5 µg.m^{-3} (Botsalano, South Africa) (Aurela et al., 2016) at background sites. Yearly mean NO_2 levels at industrial sites ranged from 5 µg.m^{-3} (Amersfoort, South Africa) (Martins et al., 2007) to 19 µg.m^{-3} (Kuraymat Egypt) (Hindy and Abdelmaksoud, 2016). A lower mean NO_2 level (12 µg.m^{-3}) was reported during January 2011 to October 2016 in the industrialised Highveld Airshed Priority Area in South Africa (Olutola & Wichmann, 2021). The yearly mean NO_2 level in 19 countries worldwide was 30.4 µg.m^{-3}, whilst the lowest mean was observed in Australia (7 µg.m^{-3}) and the highest in China (52 µg.m^{-3}) (Liu et al., 2019). The study did not report a mean for South Africa.

Daily SO_2 levels in three large South African cities ranged from 0.8 to 53.5 µg.m^{-3} in Cape Town, 3.1 to 76.9 µg.m^{-3} in Durban and 1.2 to 90.7 µg.m^{-3} in Johannesburg during 2006–2016 (Thabethe et al. 2020; Adebayo-Ojo et al., 2022). In the review by Agbo et al (2021), data on SO_2 were available for 14 countries from 23 studies. The yearly mean SO_2 levels ranged from 2–35 µg.m^{-3} at various locations in South Africa (Martins et al., 2007, Adon et al., 2010, Morakinyo et al., 2017; Laakso et al., 2012; Aurela et al., 2016; Lourens et al., 2011). The yearly mean SO_2 levels ranged from 0.8 µg.m^{-3} in Zoetele, Cameroon (Adon et al., 2010) to 10 µg.m^{-3} in Kuraymat, Egypt (Hindy and Abdelmaksoud, 2016). A lower mean SO_2 level (9 µg.m^{-3}) was reported during January 2011 to October 2016 in the industrialised Highveld Airshed Priority Area in South Africa (Olutola & Wichmann, 2021). The yearly mean SO_2 level in 16 countries worldwide was 20.2 µg.m^{-3}, whilst the lowest mean was observed in Estonia (3 µg.m^{-3}) and the highest in China (29 µg.m^{-3}) (Liu et al., 2019). The study did not report a mean for South Africa.

In the review by Agbo et al (2021), data on O_3 were available for 35 cities in 14 countries across Africa. The day time O_3 levels ranged from 0.3 µg.m^{-3} to 1.2 µg.m^{-3} in Lagos, Nigeria was (Olajire et al., 2011). The yearly mean levels ranged from 31 to 53 µg.m^{-3} at industrial locations and 69 to 71 µg.m^{-3} at background locations in South Africa (Agbo et al., 2021). O_3 levels are higher at background locations due to atmospheric chemistry. The yearly mean O_3 levels in other parts of Africa ranged from 8 µg.m^{-3} in Bomassa Congo (Adon et al., 2010) to 45 µg.m^{-3} in Okaukuejo, Namibia (Martins et al., 2007). The yearly mean O_3 level in 22 countries worldwide was 65.4 µg.m^{-3}, whilst the lowest mean was observed in Colombia (25 µg.m^{-3}) and the highest in Brazil (83 µg.m^{-3}) (Liu et al., 2019). The study did not report a mean for South Africa.

Table 2 shows the correlation between the air pollutants and temperature. PM_{10}, $PM_{2.5}$, BC, NO_2 and SO_2 had moderate positive correlations (r = 0.384 to 0.875). O_3 had inverse correlations with the other air pollutants (r= –0.258 to –0.455). Meteorological conditions can diffuse, dilute and accumulate air pollution. All the air pollutants were inversely correlated with temperature, except O_3. There was no significant correlation between temperature or Tapp and relative humidity (p>0.05). A large study of 15 African countries reported a weaker correlation between estimated $PM_{2.5}$ and BC levels (0.67) (Bachwenkizi et al. 2021). $PM_{2.5}$ and PM_{10} had a stronger correlation than those observed in 652 cities from 24 countries (0.78). A study from Cape Town reported a weaker correlation between $PM_{2.5}$ and PM_{10} (0.481) (Williams et. al.) whilst a study in the industrialised Highveld Airshed Priority Area in South Africa reported a stronger correlation (0.95) (Olutola & Wichmann, 2021). Liu et. al. (2019) reported weaker correlations between $PM_{2.5}$ and NO_2 (0.48) and between $PM_{2.5}$ and SO_2 (0.40) in 652 cities from 24 countries. Weaker correlations between $PM_{2.5}$ or PM_{10} and NO_2 or SO_2 were observed in the industrialised Highveld Airshed Priority Area (Olutola & Wichmann 2021).

Exposure-response estimates

Insignificant associations were observed between lag0-1 of PM_{10}, $PM_{2.5}$ or BC and respiratory disease hospitalisations in the unstratified analyses, i.e. entire Tapp range and all ages and sexes combined: 0.6% (95% CI -0.2%; 1.5%), 1.0% (95% CI -0.3%; 2.4%) and 1.1% (95% CI -0.1%; 2.3%), respectively (Table 3). PM_{10}, $PM_{2.5}$ and BC also did not influence hospital admissions for the different age and sex groups across the entire Tapp range, except that an increase in BC (per 1 µg.m^{-3}) lead to a significant increase of 3.6% (95% CI 0.3%; 7.0%) in hospital admissions among the elderly.

Table 2: *Spearman rank correlation coefficients between air pollution and weather variables in the Vaal Triangle Air Pollution Priority Area, South Africa, 1 January 2013 – 29 February 2020 (2616 days).*

Variable	$PM_{2.5}$	BC*	NO_2	SO2	O_3	Tapp	Temp	RH
PM_{10}	0.875	0.726	0.586	0.384	-0.258	-0.315	-0.309	-0.320
$PM_{2.5}$		0.721	0.624	0.410	-0.281	-0.320	-0.318	-0.122
BC			0.796	0.431	-0.455	-0.548	-0.539	-0.388
NO_2				0.516	-0.379	-0.433	-0.427	-0.269
SO_2					-0.335	-0.329	-0.323	-0.267
O_3						0.728	0.731	-0.111
Tapp							1.000	0.028
Temp								0.006

Abbreviations: PM_{10}: particulate matter with an aerodynamic diameter equal or smaller than 10 µm; $PM_{2.5}$: particulate matter with an aerodynamic diameter equal or smaller than 2.5 µm; BC: Black carbon; SO_2: sulphur dioxide; NO_2: nitrogen dioxide; O_3: ground-level ozone; Tapp: apparent temperature; Temp: Temperature; RH: relative humidity All correlations were significant (p < 0.001), except between temperature and RH (p=0.771), and Tapp and RH (p=0.158)

In contrast to the findings of the current study, a study from Cape Town reported a stronger association between PM_{10} and respiratory disease hospitalisations, namely a 1.9% increase in hospitalisations (95% CI 0.5%; 3.2%) per 12 µg.m^{-3} increase in lag0-1 of PM_{10}, even though the PM_{10} levels were lower than in the current study. Renzi et al. (2022) reported a weaker association between PM_{10} and daily respiratory hospitalisations than in the current study; in the entire Italy: 0.39% (95% CI 0.21%; 0.56%) per 10 µg.m^{-3} increase in lag0-1 of PM_{10}. PM_{10} levels ranged from 2 to 290 µg.m^{-3} in their study. A meta-analysis on studies conducted in LMIC reported the same percentage increase in daily respiratory disease hospitalisation per 10 µg.m^{-3} increase in lag0-1 of PM_{10} as the study from Italy (Newell et al., 2017). Most of these studies were from East Asia and the Pacific region.

Atkinson et al (2014) conducted the most recent systematic review and meta-analyses on the effects of $PM_{2.5}$ on daily respiratory disease hospitalisations. They reviewed 43 time-series epidemiological studies; none were from Africa. An excess risk of 0.96% (95% CI −0.63%; 2.58%) was reported per 10 µg.m^{-3} increase in lag0-1 of $PM_{2.5}$, which is similar to our result. A lower increase in daily respiratory disease hospitalisation per 10 µg.m^{-3} increase in lag0-1 of $PM_{2.5}$ was observed in LMIC, namely 0.42% (95% CI –0·93; 1·77) (Newell et al., 2017).

Very few studies globally and none from Africa investigated the short-term effects of BC on respiratory disease hospital admissions. Song et al (2021) reported a 1.2% (95% CI 0.7%; 3.1%) increase in respiratory disease hospital admissions per 1 µg.m^{-3} increase in BC (10 studies), which is similar to our observation.

Increases in the three gaseous air pollutants (NO_2, SO_2 and O_3) significantly increased hospital admissions across the entire Tapp range and for all population groups combined: 3.0% (95%

CI 1.3%; 4.7%), 1.7% (95% CI 0.1%; 3.4%) and 2.5% (95% CI 0.9%; 4.3%) per 10 μg.m^{-3} increase in lag0-1 levels, respectively. A study from Cape Town reported similar associations between NO_2 or SO_2 and respiratory disease hospitalisations, namely a 2.3% (95% CI 0.6–4%), and 1.1% (95% CI −0.2–2.4%) increase per 7.3 μg.m^{-3} or 3.6 μg.m^{-3} increase in lag0-1 of NO_2 or SO_2, respectively. NO_2 and SO_2 levels were lower in Cape Town. Across the entire Tapp range, the elderly was significantly most at risk for hospitalisation when NO_2 increased (8.2% 95% CI 3.4; 13.2) whilst this was the case for the 15–64 year old group when O_3 increased (3.8% 95% CI 1.0; 6.7).

In general, an increase in the air pollutants on days with moderate Tapp significantly lead to more admissions compared those on low and high Tapp days, except for NO_2 and O_3 that resulted in significantly more admissions on days with warm Tapp (Table 3). An unexpected result was the 1.3% and 1.9% reduction in respiratory disease hospital admissions with increasing levels of PM_{10} on days with low Tapp for all groups combined and the youngest age group, respectively. The elderly was more vulnerable when the air pollutants increased, especially with increases in SO_2 on days with moderate Tapp that lead to a significant 17.1% increase in hospitalisations. Females were more at risk to be hospitalised than males when PM_{10}, $PM_{2.5}$ or BC increased on days with moderate Tapp. Males were more at risk than females when NO_2 or SO_2 increased on days with moderate Tapp or when O_3 increased on days with warm Tapp.

NO_2 and SO_2 in general had stronger associations with hospital admissions compared to PM_{10}, $PM_{2.5}$ and BC on days with moderate Tapp. In general, $PM_{2.5}$ and PM_{10} are regarded to be the most hazardous of the criteria air pollutants as they infiltrate to the lower airways and consist of many toxic components that trigger a variety of adverse health responses such as inducing oxidative stress in the airways, inflammatory responses and impairing the immune system (Li et al., 2022). A plausible reason for the higher hospitalisation risks of NO_2 compared to PM_{10} may be due to the fact that NO_2 is a precursor for ions of water-

Table 3: *Percentage change (95% CI) in daily respiratory disease hospital admissions in Vereeniging and Vanderbijlpark, South Africa following an increase in an air pollutant level (lag0-1) in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 – 29 February 2020 (2616 days).*

Air pollutant	Tapp	All	0–14 years	15–64 years	≥65 years	Females	Males
PM_{10}	Entire range	0.6 (-0.2; 1.5)	0.9 (-0.3; 2.1)	-0.3 (-1.7; 1.2)	2.0 (-0.4; 4.4)	0.6 (-0.6; 1.8)	0.6 (-0.6; 1.9)
	Low	**-1.3 (-2.4; -0.1)**	**-1.9 (-3.5; -0.3)**	-0.6 (-2.5; 1.3)	-0.7 (-3.7; 2.5)	-1.3 (-2.8; 0.3)	-1.3 (-2.9; 0.3)
	Medium	**3.3 (1.7; 5.0)**	**4.2 (2.0; 6.5)**	0.5 (-2.1; 3.3)	**7.7 (2.8; 13.0)**	**3.5 (1.2; 5.8)**	**3.1 (0.8; 5.5)**
	High	-1.9 (-5.2; 1.6)	-0.2 (-5.0; 4.7)	-2.9 (-8.1; 2.6)	-3.0 (-12.1; 7.0)	-2.5 (-7.1; 2.3)	-1.2 (-5.9; 3.7)
$PM_{2.5}$	Entire range	1.0 (-0.3; 2.4)	1.0 (-0.8; 2.9)	0.3 (-1.9; 2.5)	3.4 (-0.4; 7.3)	1.3 (-0.5; 3.2)	0.8 (-1.1; 2.7)
	Low	-1.1 (-2.8; 0.6)	-2.2 (-4.6; 0.2)	-0.2 (-3.0; 2.7)	0.7 (-4.0; 5.6)	-0.8 (-3.2; 1.7)	-1.5 (-3.9; 1.0)
	Medium	**4.2 (1.5; 6.9)**	**5.2 (1.5; 9.0)**	0.4 (-3.9; 5.0)	**10.7 (2.3; 19.8)**	**4.6 (0.9; 8.6)**	3.6 (-0.2; 7.6)
	High	1.1 (-4.0; 6.5)	3.5 (-3.9; 11.5)	0.2 (-7.7; 8.9)	-1.8 (-15.2; 13.8)	3.7 (-3.6; 11.5)	-1.4 (-8.3; 6.0)
Black carbon	Entire range	1.1 (-0.1; 2.3)	1.4 (-0.3; 3.0)	-0.1 (-2.0; 1.8)	**3.6 (0.3; 7.0)**	1.3 (-0.3; 3.0)	0.8 (-0.8; 2.5)
	Low	-1.5 (-3.0; 0.0)	-2.7 (-4.9; -0.6)	-0.8 (-3.2; 1.7)	1.4 (-2.7; 5.6)	-0.9 (-3.0; 1.3)	-2.1 (-4.2; 0.1)
	Medium	**4.9 (2.6; 7.2)**	**6.8 (3.7; 9.9)**	1.0 (-2.7; 4.8)	**7.8 (1.0; 15.1)**	**5.0 (1.9; 8.3)**	**4.7 (1.5; 8.0)**
	High	1.5 (-4.4; 7.7)	5.8 (-2.8; 15.1)	-3.4 (-12.2; 6.4)	2.8 (-13.4; 22.1)	2.9 (-5.3; 11.9)	-0.1 (-8.3; 8.8)
NO_2	Entire range	**3.0 (1.3; 4.7)**	**3.5 (1.2; 5.9)**	0.5 (-2.1; 3.3)	**8.2 (3.4; 13.2)**	**2.7 (0.4; 5.1)**	**3.2 (0.8; 5.6)**
	Low	-1.3 (-3.5; 1.1)	-3.4 (-6.6; 0.0)	-0.3 (-4.0; 3.6)	4.1 (-2.2; 10.9)	0.0 (-3.3; 3.3)	-2.5 (-5.7; 0.9)
	Medium	**7.8 (4.9; 10.8)**	**9.8 (5.8; 14.0)**	3.2 (-1.4; 8.0)	**14.2 (5.4; 23.6)**	**6.7 (2.8; 10.9)**	**8.9 (4.8; 13.3)**
	High	**8.7 (0.9; 17.1)**	**14.5 (3.1; 27.2)**	2.9 (-8.8; 16.1)	6.4 (-14.5; 32.4)	2.8 (-7.4; 14.1)	**15.4 (3.7; 28.4)**
SO_2	Entire range	**1.7 (0.1; 3.4)**	2.0 (-0.3; 4.3)	1.2 (-1.5; 3.9)	2.2 (-2.4; 7.1)	1.5 (-0.8; 3.8)	1.9 (-0.4; 4.3)
	Low	-1.5 (-3.9; 1.1)	-1.4 (-4.9; 2.2)	-0.1 (-4.1; 4.1)	-5.3 (-11.7; 1.6)	-0.5 (-4.0; 3.1)	-2.5 (-5.9; 1.1)
	Medium	**6.5 (3.4; 9.6)**	**5.6 (1.5; 9.9)**	4.6 (-0.4; 9.9)	**17.1 (7.5; 27.4)**	**5.1 (0.9; 9.5)**	**7.9 (3.5; 12.4)**
	High	-0.1 (-5.1; 5.1)	2.8 (-4.4; 10.5)	-2.2 (-9.8; 5.9)	-4.4 (-18.1; -11.6)	-4.0 (-10.5; 3.1)	4.2 (-3.1; 12.0)
O_3	Entire range	**2.5 (0.9; 4.3)**	1.9 (-0.4; 4.3)	**3.8 (1.0; 6.7)**	1.5 (-3.2; 6.5)	**2.6 (0.3; 5.1)**	2.4 (0.0; 4.9)
	Low	1.0 (-2.9; 4.9)	0.5 (-4.9; 6.3)	0.3 (-5.8; 6.7)	5.2 (-5.5; 17.0)	0.4 (-5.0; 6.0)	1.5 (-3.9; 7.3)
	Medium	1.1 (-1.5; 3.7)	0.9 (-2.6; 4.5)	1.3 (-3.0; 5.9)	0.7 (-6.6; 8.4)	2.6 (-1.0; 6.4)	-0.6 (-4.2; 3.2)
	High	**5.2 (1.6; 9.0)**	5.1 (-0.1; 10.5)	5.5 (-0.3; 11.6)	4.8 (-5.6; 16.4)	4.9 (-0.2; 10.2)	**5.6 (0.4; 11.1)**

High: Apparent temperature > 75th percentile; Low: Apparent temperature < 25th percentile; Medium: Apparent temperature >= 25th and <= 75th percentile. Abbreviations: PM_{10}: particulate matter with an aerodynamic diameter equal or smaller than 10 μm; $PM_{2.5}$: particulate matter with an aerodynamic diameter equal or smaller than 2.5 μm; SO_2: sulphur dioxide; NO_2: nitrogen dioxide; O_3: ground-level ozone; Tapp: apparent temperature; Bold text: Significant ($p < 0.05$)

soluble inorganic salts, such as nitrate, that can partition to the particulate-phase, thus generating PM (WHO, 2013). A review reported that all-cause non-accidental mortality increased by 17% per 1 $\mu g.m^{-3}$ increase in nitrate (Atkinson et al. 2015), compared to a 0.4% increase per 10 $\mu g.m^{-3}$ increase in PM_{10} (Orellano et al., 2020). SO_2 is converted to sulphate- during the afternoon when sunlight is brightest (He et al. 2014). Sulphate leads to a substantial increase in the bioavailable metals and soot in PM (WHO, 2013). A review concluded that natural-cause mortality increased by 15% per 1 $\mu g.m^{-3}$ increase in sulphate (Atkinson et al. 2015).

BC and $PM_{2.5}$ had stronger associations than PM_{10} with hospital admissions on days with moderate Tapp (Table 3). On a mass basis, BC has a greater relative toxicity compared to $PM_{2.5}$ (Janssen et al., 2011; Thomas et al., 2017), and this was also observed in our study with BC having, in general, stronger associations with respiratory disease hospital admissions compared to $PM_{2.5}$. BC make up a small proportion of total $PM_{2.5}$ mass and air pollution abatement strategies targeted at lowering BC sources may assist to diminish the health effects attributed to $PM_{2.5}$, although only to a small extent (Thomas et al., 2017). $PM_{2.5}$ penetrate deeper into the lungs than PM_{10}, which is a possible explanation for the higher risks observed for hospitalisation. Another possible reason is that the two air pollutants often have different sources which influences the chemical composition. $PM_{2.5}$ is also a subfraction of PM_{10}. $PM_{2.5}$ derive from combustion sources or from atmospheric chemistry reactions, whilst the coarse fraction of PM_{10} derive from dust. A review included in the 2021 WHO AQ Guideline report, also observed higher risks for $PM_{2.5}$ than PM_{10} in terms of daily all-cause non-accidental mortality (Orellano et al., 2020).

More studies investigated effect modification of temperature indicators, such as Tapp, on the effects of air pollution on mortality than hospitalisations (Chen et al., 2017; Li et al., 2017; Lokotola et al., 2020; Grigorieva and Lukyanets, 2021; Areal et al., 2022). Studies that focused on mortality mostly defined days with cold, moderate and warm Tapp as done in this study, i.e. used the 25th and 75th percentiles of Tapp as cut-off points (Chen et al. 2017; Li et al. 2017, Lokotola et al. 2020; Olutola and Wichmann, 2021; Shirinde and Wichmann, 2022). However, the selection of the cut-off points is arbitrary. Five studies applied different percentile cut-off values (10th, 15th, 20th, 25th, 50th, 75th, 80th, 85th, 90th) to define days with low, moderate and high temperature (Wang et al., 2013; Qui et al., 2018; Yitshak-Sade et al., 2018; Lokotola et al., 2020; Olutola & Wichmann, 2021; Areal et el., 2022). Some studies focused on specific respiratory disease hospital admissions such as chronic obstructive pulmonary disease (COPD), and none of the studies investigated BC or O_3. The range of air pollutant and temperature levels also varied across studies. Comparing results is therefore a challenge.

Wang et al (2013) conducted a study in Lanzhou City, China and focused on respiratory disease hospitalisations amongst all ages, PM_{10}, SO_2 and NO_2 during 2001–2005. The strongest associations for all three pollutants were observed on days with low temperature (<15th percentile), followed by days with moderate temperature and high temperature (>85th percentile). Wang et al (2013) did not investigate $PM_{2.5}$, O_3 or BC. Air pollution levels were higher in Lanzhou City than in the current study, as PM_{10} levels ranged from 16 to 2561 $\mu g.m^{-3}$, NO_2 from 4 to 260 $\mu g.m^{-3}$ and SO_2 from 2 to 371 $\mu g.m^{-3}$. Lower temperatures were reported than in the current study, whilst the maximum was similar (range -12 to 30°C).

Qui et al (2018) investigated COPD hospitalisations amongst all ages in urban areas of Chengdu, China during 2015–2016. The strongest associations for PM_{10}, $PM_{2.5}$, NO_2 and SO_2 were observed on days with low temperature (<20th percentile), followed by days with high temperature (≥80th percentile) and moderate temperature. Qui et al (2018) did not investigate O_3 or BC. Air pollution levels were higher in the urban areas of Chengdu than in the current study, as PM_{10} levels ranged from 13 to 339 $\mu g.m^{-3}$ and NO_2 from 14 to 106 $\mu g.m^{-3}$. Similar temperature levels were reported than in the current study, namely from -1 to 30°C.

As in the study by Wang et al (2013), the current study also observed the higher hospitalisation risks for PM_{10} and SO_2 on days with moderate Tapp compared to days with high Tapp. However, our results differ from Qui et al (2018) and Wang et al (2013) as the strongest associations between hospitalisations and air pollutants were not observed on days with cold Tapp, but on days with moderate Tapp.

Yitshak-Sade et al (2018) investigated the association between $PM_{2.5}$ and respiratory disease hospitalisations amongst the elderly (≥65 years) in New-England, USA during 2001–2011. They observed the strongest association on days with high temperature (>90th percentile). In contrast the strongest association was observed on days with moderate Tapp in the current study. The $PM_{2.5}$ and temperature levels were higher in the current study than in New England as the interquartile range of $PM_{2.5}$ was 5 to 11 $\mu g.m^{-3}$ and for temperature 6 to 15 °C.

Olutola & Wichmann (2021) and Lokotola et al. (2020) investigated the association between respiratory disease hospitalisations amongst all ages and PM_{10}, NO_2 and SO_2 during January 2011 to October 2016 in the industrialised Highveld Airshed Priority Area and in Cape Town, respectively. In both studies the effects of the three air pollutants on hospitalisation were more pronounced on days with high Tapp (>75th percentile), as was the case in the study by Yitshak-Sade et al (2018).

None of the studies that focused on respiratory disease hospital admissions investigated BC or O_3, whilst the few studies that investigated mortality assessed O_3, but not BC. Three studies conducted in the China, UK and US reported stronger associations between O_3 and all-cause non-accidental or respiratory disease mortality on days with high temperature compared to days with low or moderate temperature (Pattenden et al., 2010; Qian et al., 2008; Ren et al., 2008). This is in agreement with the results of the current study.

Meteorology, toxicity of air pollutants, atmospheric chemistry, human behaviour or physiology are plausible reasons why temperature indicators may modify the effects of air pollution on health outcomes. The likelihood to be exposed to outdoor air pollution may be higher on days with moderate and high Tapp levels as people may spend more time outdoors or may open windows more resulting in more outdoor air pollution infiltrating indoors. Similarly, the likelihood of exposure to outdoor air pollution may be lower on days with low Tapp levels as people may spend more time indoors and may keep windows closed. The sources and composition of air pollution may fluctuate with outdoor temperature. A greater fraction of more toxic forms of PM at higher temperature were reported by studies (Li et al., 2017; Chen et al., 2017). The possible biological mechanisms for the synergistic effects between air pollution and high temperature on human health were summarised in a review (Grigorieva and Lukyanets, 2021). Mechanisms of thermoregulation may play a role to increase the inhaled dose of air pollutants and increased dose absorbed by the skin. A combination of air pollution and heat exposure is associated with systemic inflammation and lung tissue damage (Grigorieva and Lukyanets, 2021).

Inconsistent results were reported for risks by age and sex. In the current study the elderly (≥65 years) and females were in general more vulnerable to air pollution exposure. Females have smaller lung tissue and trachea than males, which may lead to a greater inhaled dose (Oiamo and Luginaah, 2013). Women have a higher working metabolic rate, sweat less and may have thicker subcutaneous fat that may hamper thermoregulation (Kazman et al., 2015). In contrast, Olutola & Wichmann (2021) and Lokotola et al. (2020) observed the youngest group (0-14 years) to be more at risk to air pollution exposure, whilst Qui et al (2018) reported the elderly (≥80 years) to be more vulnerable. Wang et al (2013) noted that the <65 year old group was more at risk than the older age group. All the other studies reported that males were more vulnerable to air pollution.

This study is not without limitations. As in similar studies, the assumption that the ambient air pollution and meteorological variables measured at a few sites are the same across the entire area might have resulted in a measurement error. This exposure misclassification is non-differential and bias associations to be insignificant (i.e. bias effect estimates towards the null) (Hatch and Thomas, 1993). This study cannot be extrapolated to the general South African population as the study applied private hospital data and the patients belong to the middle and upper socio-economic classes. Only the wealthiest 16% of the South African population make use of the private-sector services (Barber et al., 2018). Perhaps effects may be even worse if data from public hospitals were available as mostly patients in the lower socio-economic classes make use of public hospitals. Poverty and malnutrition may make them more susceptible to the health risks of air pollution.

Conclusions

The aim of this study was to determine whether the association between RD hospitalisations and air pollution in the VTAPA was modified by Tapp during January 2013 to February 2020. It was observed that air pollution effects on respiratory disease hospitalisation were indeed modified by Tapp. In general, moderate Tapp worsened the effects of $PM_{2.5}$, PM_{10}, SO_2 and BC, whilst the effects of NO_2 and O_3 were most pronounced on days with high Tapp. The elderly and females were more vulnerable to air pollution, especially on days with moderate Tapp. Globally more epidemiological studies are needed on this topic.

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Author contributions

NSW: methodology; data collection; data analysis; data curation; writing. BGO: conceptualisation; methodology; writing. JW: conceptualisation; methodology; data collection; data analysis; data curation; writing.

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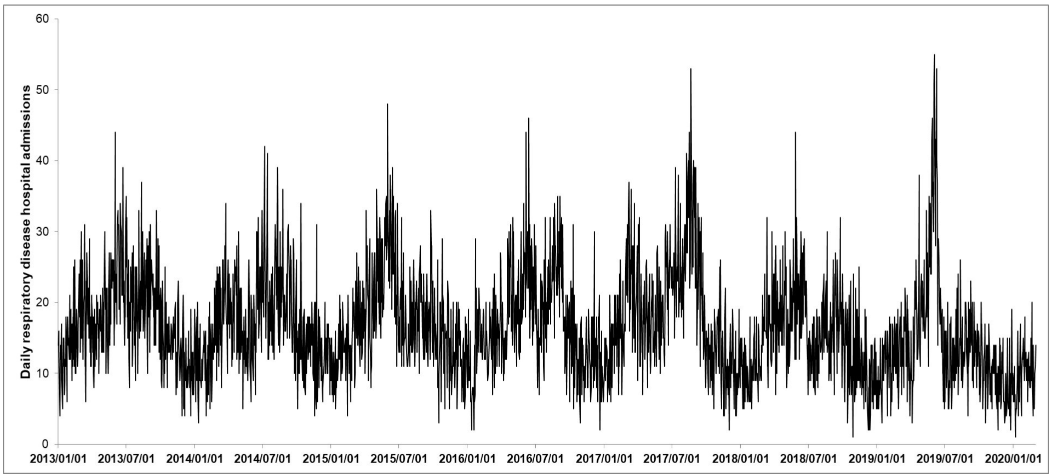
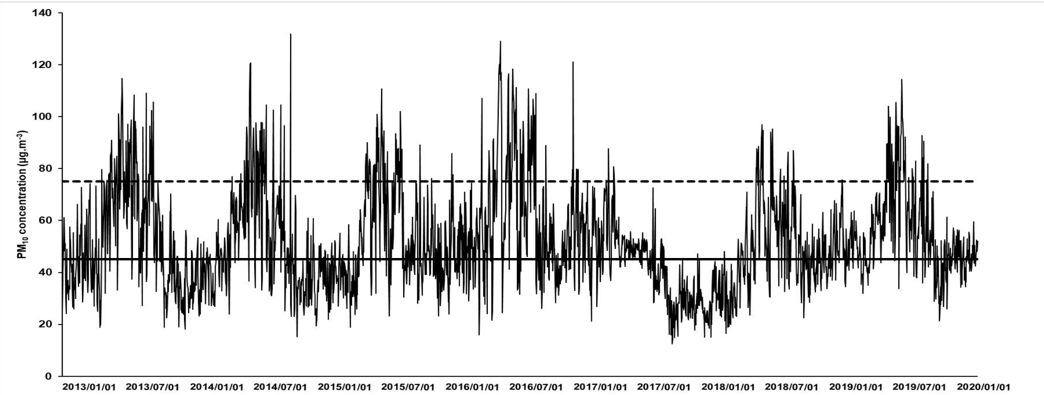


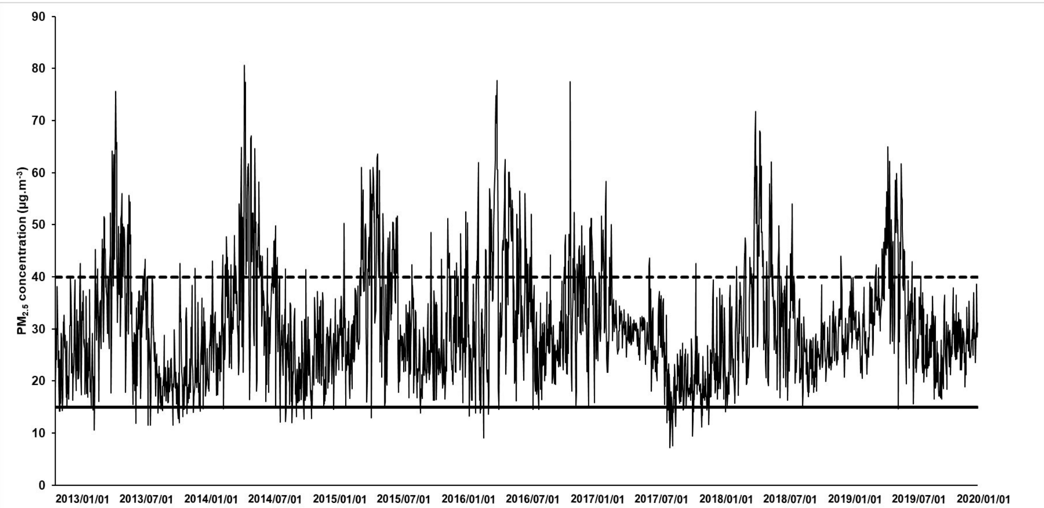
Supplementary Figure 1: *Time-series of the daily number of respiratory disease hospital admissions in Vanderbijlpark and Vereeniging in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*



Supplementary Figure 2: *Time-series of the daily levels of PM$_{10}$ in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

Solid line: Daily WHO guideline (45 µg.m^{-3})

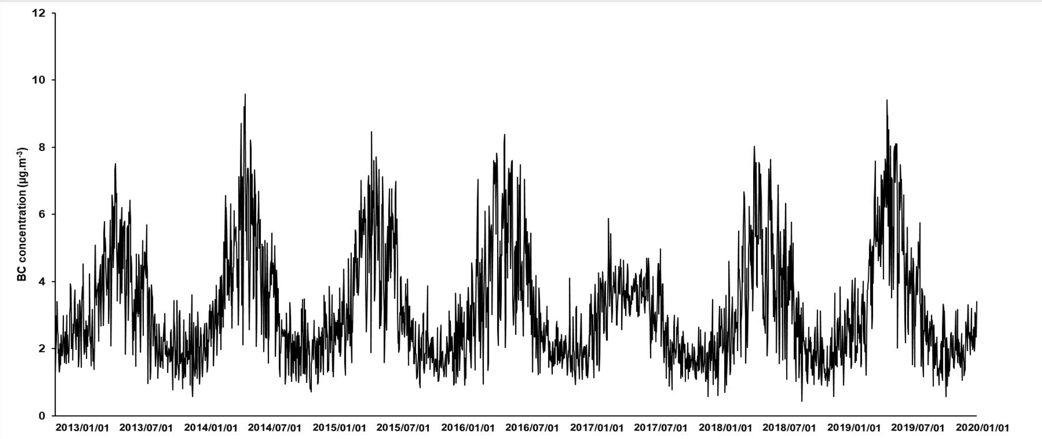
Dotted line: Daily South African standard (75 µg.m^{-3})



Supplementary Figure 3: *Time-series of the daily levels of PM$_{2.5}$ in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

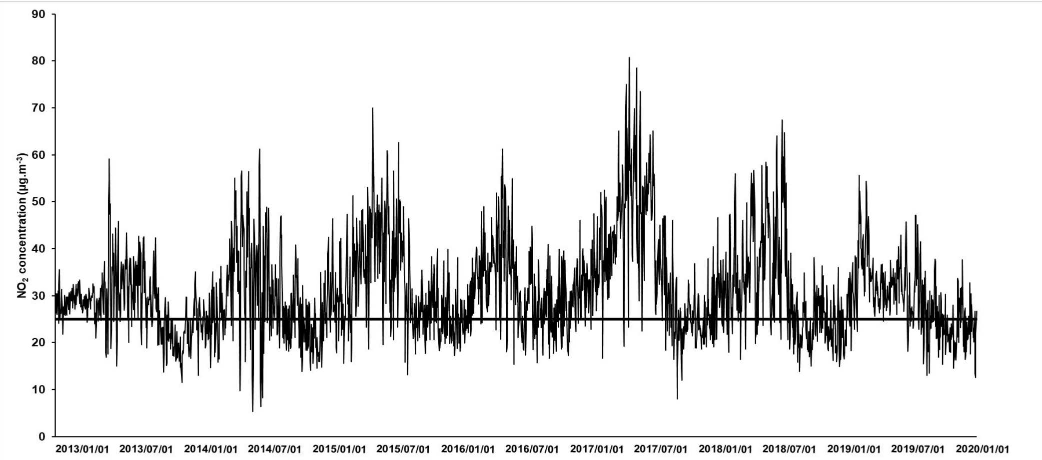
Solid line: Daily WHO guideline (15 µg.m^{-3})

Dotted line: Daily South African standard (40 µg.m^{-3})



Supplementary Figure 4: *Time-series of the daily levels of BC in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

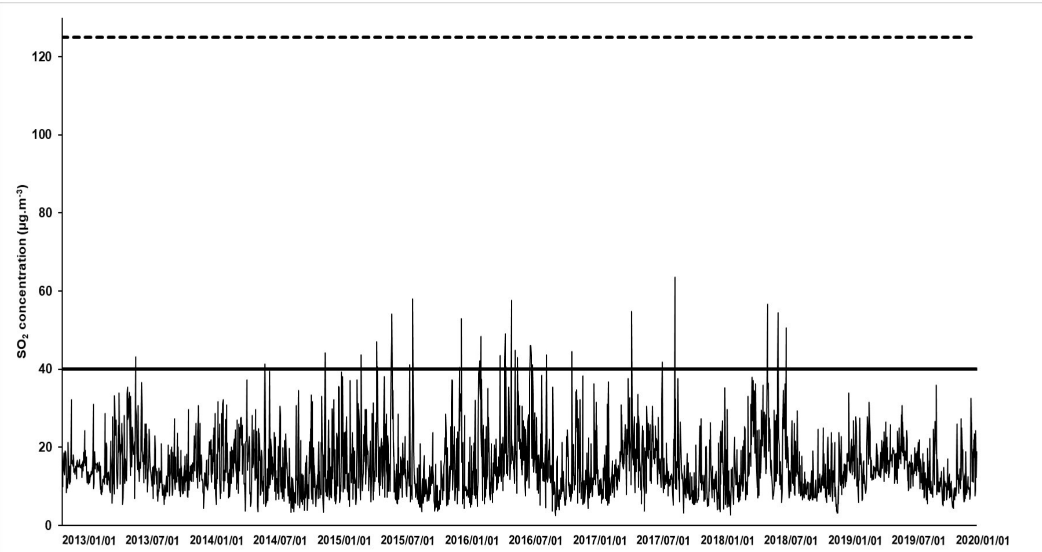
There is no daily WHO guideline or South African standard for BC



Supplementary Figure 5: *Time-series of the daily levels of NO_2 in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

Solid line: Daily WHO guideline (25 μg.m^{-3})

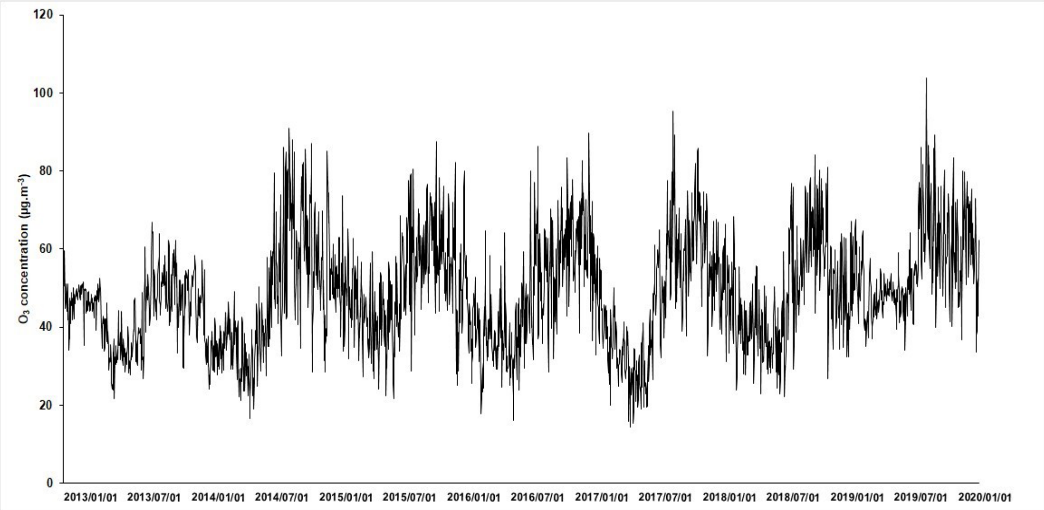
There is no daily South African standard for NO_2



Supplementary Figure 6: *Time-series of the daily levels of SO_2 in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

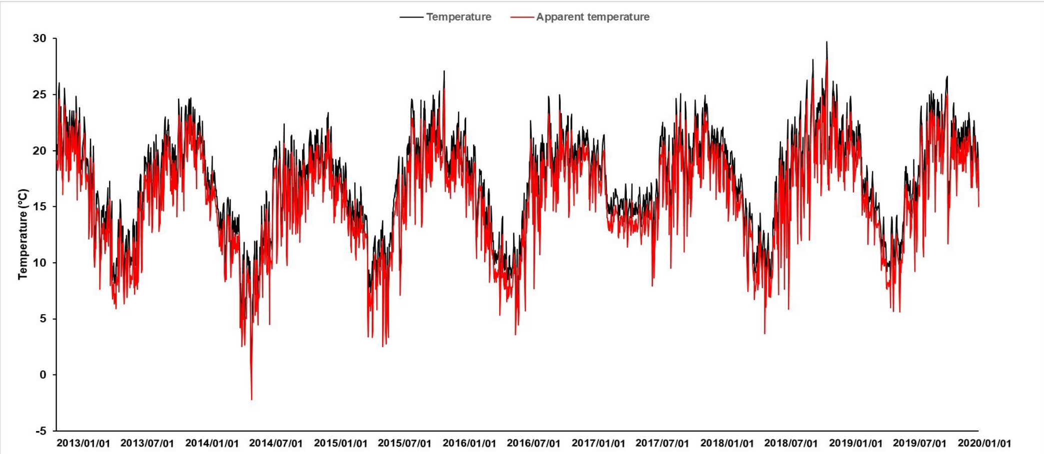
Solid line: Daily WHO guideline (40 μg.m^{-3})

Dotted line: Daily South African standard (125 μg.m^{-3})

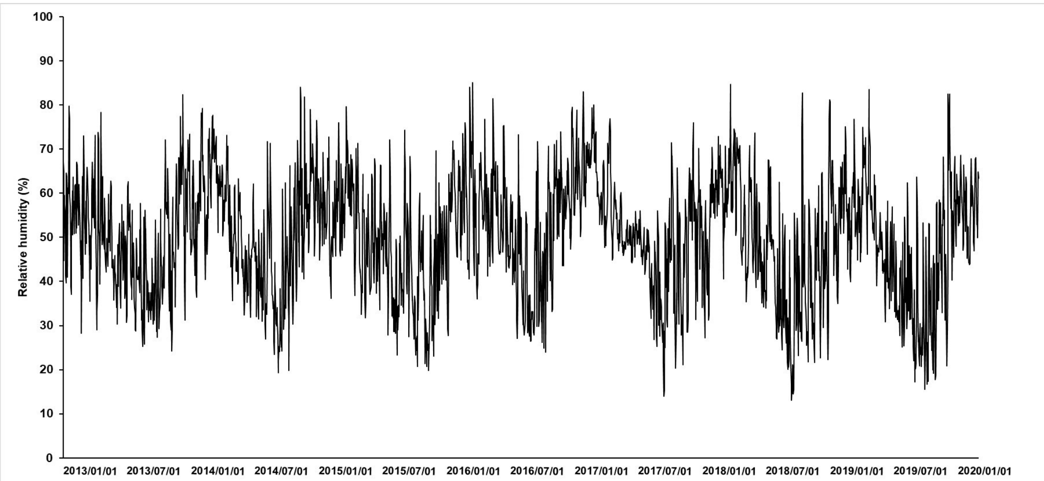


Supplementary Figure 7: *Time-series of the daily levels of O_3 in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*

There is no daily WHO guideline or South African standard for O_3



Supplementary Figure 8: *Time-series of the daily levels of temperature and apparent temperature in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*



Supplementary Figure 9: *Time-series of the daily levels of relative humidity in the Vaal Triangle Air Pollution Priority Area, South Africa during 1 January 2013 to 29 February 2020.*


ENVIRONMENTAL SERVICES
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Eskom drives just energy transition for a greener future in energy

Eskom has embarked on a Just Energy Transition drive to reduce its carbon footprint, while at the same time promoting local industrialisation and ensuring that no jobs are lost in the process.

Given that some of its coal power stations are approaching the end of their life, this is the ideal opportunity to increase capacity with clean technologies by repowering and repurposing our stations. This in turn will contribute to continued economic stimulus, particularly in the communities close to the stations.

Eskom will be seeking to secure significant financing to support its accelerated transition away from coal, increase clean capacity and to protect workers, communities and businesses whose livelihoods are threatened by the shutdown programme.

André de Ruyter, Eskom Group Chief Executive, has indicated that several "repowering and repurposing" opportunities have already been identified.

Pilot project

The Camden, Komati, Grootvlei and Hendrina power stations are scheduled for shutdown in the near-term. Komati has been generating electricity since 1961, and its last operational unit is scheduled to be shut down in 2022, signalling the start of a coal shutdown programme.

Among other opportunities, Eskom is planning to convert the workshops at the Komati power station in Mpumalanga to a factory that will manufacture and assemble a containerised microgrid solution. Eskom has already piloted a microgrid system near Ficksburg in the Free State. This consists of solar photovoltaic (PV) generation, battery storage and intelligent energy management. These technologies have been integrated into a standard, low-voltage reticulation network, where electricity is delivered to consumers through conductor wires in a local distribution network.

The containerised microgrid solutions could be deployed in far-flung regions nationally where grid-tied electricity is proving to be hugely expensive to supply. There is also great potential to market it to the rest of Africa where, in many cases, the percentage of electrified homes is much lower than in South Africa.

Besides the microgrid manufacturing, Eskom is also working on repowering options through the deployment of solar PV and battery storage.

A major concern related to the shutdown of coal stations is job losses at the stations and linked mines as well as communities near the power stations. Eskom has conducted extensive socio-economic impact studies at Komati, Grootvlei and Hendrina to understand these impacts, and ensure that a robust plan is developed in collaboration with social partners, to manage these negative impacts. We will be conducting these studies for each of our coal stations as they approach shutdown.

As Eskom transitions away from coal, it estimates that nearly 300 000 net jobs could be created in the construction, operation and maintenance of new Eskom and non-Eskom wind and solar PV plants. This figure is based on the assumption that South Africa will grow the local manufacturing ability and attract the investment needed to produce wind and solar components.

Eskom has a comprehensive JET Strategy that details additional opportunities such as battery storage.

Eskom implemented this microgrid in the Free State as a pilot project

Komati Power Station in Mpumalanga

Just: Doing better for people and the planet, and growing localisation

Energy: Cleaner, sustainable electricity provision

Transition: Transformational change of business models, attracting green financing

Research article

The use of fire radiative power observations to determine spontaneous combustion event activities associated with coal mining on the Mpumalanga Highveld

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Abstract

Coal mining is a significant activity on the Mpumalanga Highveld. One of the major air pollution issues associated with coal mining, is the spontaneous combustion of coal. There are no abatement technologies in place for such emissions, and typically long- and short-lived greenhouse gases, other gaseous pollutants and particulate matter are emitted by such events. For ambient air quality models to accurately capture the contribution of spontaneously combusted coal, it is necessary to determine the locations and durations of these burning events. Such information will also assist in explaining experimentally determined ambient air quality data. In this article, satellite fire radiative power (FRP) data from the Moderate Resolution Imaging Spectro-Radiometer (MODIS) was used to determine the locations and durations of spontaneously combusted coal within the Mpumalanga Highveld for January 2001 to December 2019. From the results it was concluded that five mining sites were prone to spontaneous combustion. These sites were all opencast mines situated on old bord and pillar mines. Two of these areas were actively burning for most of the 19-year study period. A relatively well-defined seasonal pattern was also observed, with combustion events being more prevalent during the winter months. Considering the active burning periods of the areas where spontaneous combustion were recorded, it is obvious that this is a major source of atmospheric pollutants on the Mpumalanga Highveld.

Keywords

Spontaneous coal combustion, coal mining, MODIS, fire radiative power

Introduction

Spontaneous combustion of coal is prevalent in the coal mining industry and happens as coal is exposed to oxygen (Pone et al. 2007). This phenomenon is of global concern as these burning events contribute to global warming, the degradation of air quality and pose other significant environmental problems (Pone et al. 2007). Many of the same pollutants are emitted by the spontaneous combustion of coal, as from coal-fired power plants (Sloss 2013). However, because there are no abatement technologies in place for these events, the emission factors are in general higher (Sloss, 2013). Greenhouse gases (GHG's) such as carbon dioxide (CO_2) and methane (CH_4), equivalent black carbon (eBC, definition according to Petzold et al., 2013) and other atmospheric pollutants like particulate matter (PM), carbon monoxide (CO), mercury, oxides of nitrogen (NO_x), oxides of sulphur (SO_x), hydrogen sulphide (H_2S) and volatile organic compounds (VOC's) are typically emitted by spontaneous combustion of coal (Stracher and Taylor 2004; Pone et al. 2007; Carras et al. 2009; Zhen-qi et al. 2009; Sloss 2013).

In South Africa, a significant fraction of coal mining activities take place in the Mpumalanga Highveld. Coal mining activities typically include open-cast mines, coal refuse disposal areas and open-cast mining operations above old bord and pillar mining operations. The latter being known for spontaneous combustion of coal as old bord and pillar workings are re-mined and exposed to oxygen (Bell et al. 2001; Pone et al. 2007).

Considering the aforementioned, it is of utmost importance to determine where spontaneous combustion of coal is taking place, for how long these activities take place and to estimate the contribution of these burning emissions on air quality.

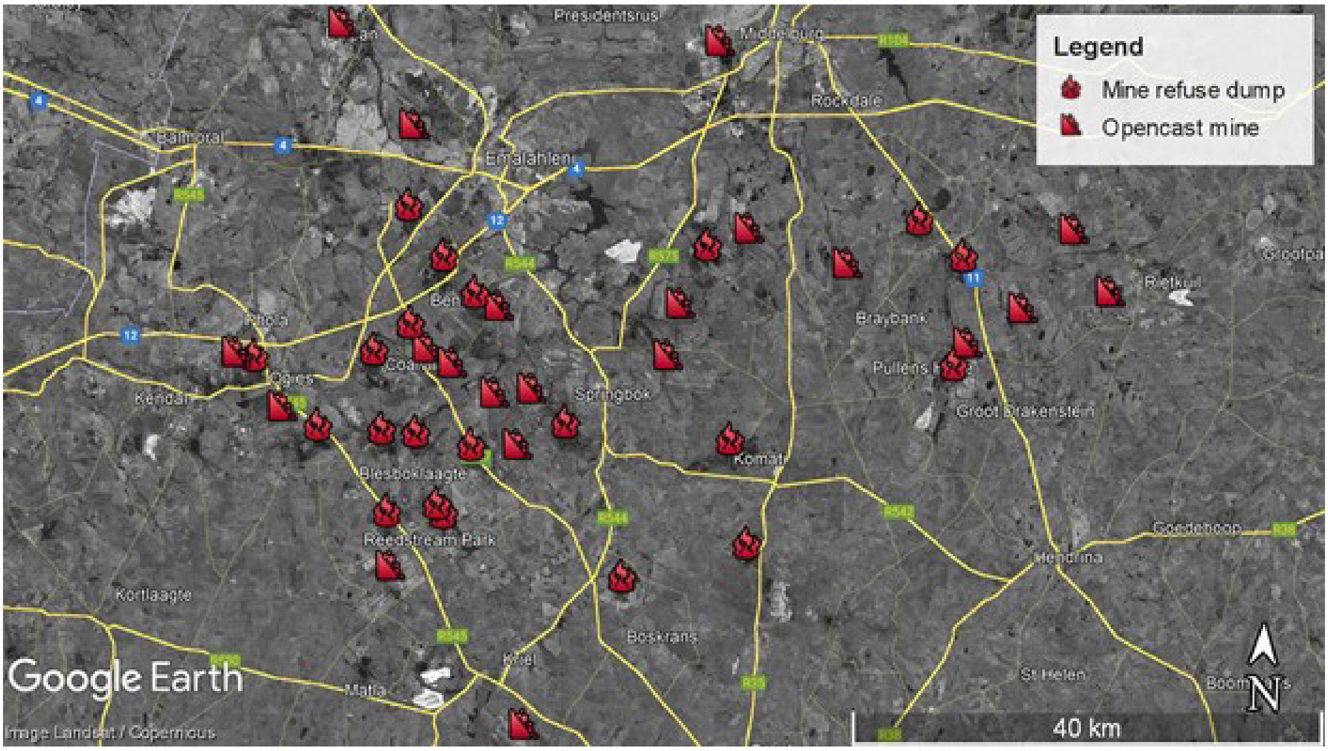

Figure 1: *Map indicating the area under investigation within the context of South Africa, as well as a Google Earth image presenting the locations of various opencast coal mines and coal refuse dumps.*

However, doing this is problematic as many of these combustion events occur in remote areas and some even go by unnoticed. Thus, in this article the fire radiative power (FRP) data obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites (Kaufman et al. 1998; Justice et al. 2002) were used to determine the location and number of burning events from January 2001 to December 2019 within the Mpumalanga Highveld region. A similar method was used by Beukes et al. (2018) to identify and determine the activities of pyro-metallurgical smelters within South Africa. In Figure 1 the region in South Africa, more specifically the Mpumalanga Highveld, under investigation is presented with a Google Earth map. Within this area, the locations of open-cast coal mining operations, as well as mine refuse dumps, were derived from rigorous visual inspection of Google Earth images and are presented in the Google Earth map.

Method

Identification of spontaneous coal combustion

FRP data was obtained from the MODIS instruments aboard the Terra and Aqua satellites for the period of January 2001 to December 2019 (Kaufman et al. 1998; Justice et al. 2002). The MODIS collection 6 FRP data was downloaded from the Fire Information for Resource Management System archives (https://firms.modaps.eosdis.nasa.gov/download/). MODIS FRP data (MOD14A1/MYD14A1) indicate the locations of fires with substantial thermal emissions at times when the satellites pass over the area. These thermal emissions are usually from open biomass burning events (grassland, savannah and forest fires), but certain point sources with substantial thermal emissions (e.g. metal/slag tapping or off-gas flaring from pyrometallurgical smelters) are also detected as thermal anomalies (Beukes et al. 2018). Considering the thermal emissions from spontaneous coal combustion, these burning events could also be captured in the FRP data, depending on the fire size (m^2) and temperature (°C). MODIS easily detects smouldering and flaming landscape fires of a 1000 m^2 in size. However, if conditions are favourable, fires as small as 50 m^2 can be detected. On the other hand, false alarms are possible, but rare especially for southern Africa (Giglio et al., 2016). In our application, where we are looking for sites with continuous combustion for weeks or more, occasional false positive FRP observations are not an issue. Giglio et al. (2003) discusses the probability of detection in further detail.

In Figure 2 an example of the FRP data is depicted, with red dots indicating fires recorded for February and March 2016. Each red dot represents a burning activity recorded in a 1 km^2 cell. A Google Earth image of the encircled area indicated in Figure 2 is also presented. Numerous detected fires can be seen in Figure 2, as well as thermal anomalies at industrial facilities. Within the encircled area in Figure 2, 6 pixels (at 1 km resolution) indicate continuous combustion for two consecutive months and 3 more pixels indicate combustion part of the time. It is obviously impossible for the same vegetation to be actively burning constantly for months on end, as the fuel required for combustion will mostly be consumed after one burning event. Additionally, the timing of the fires (i.e., in February and March)

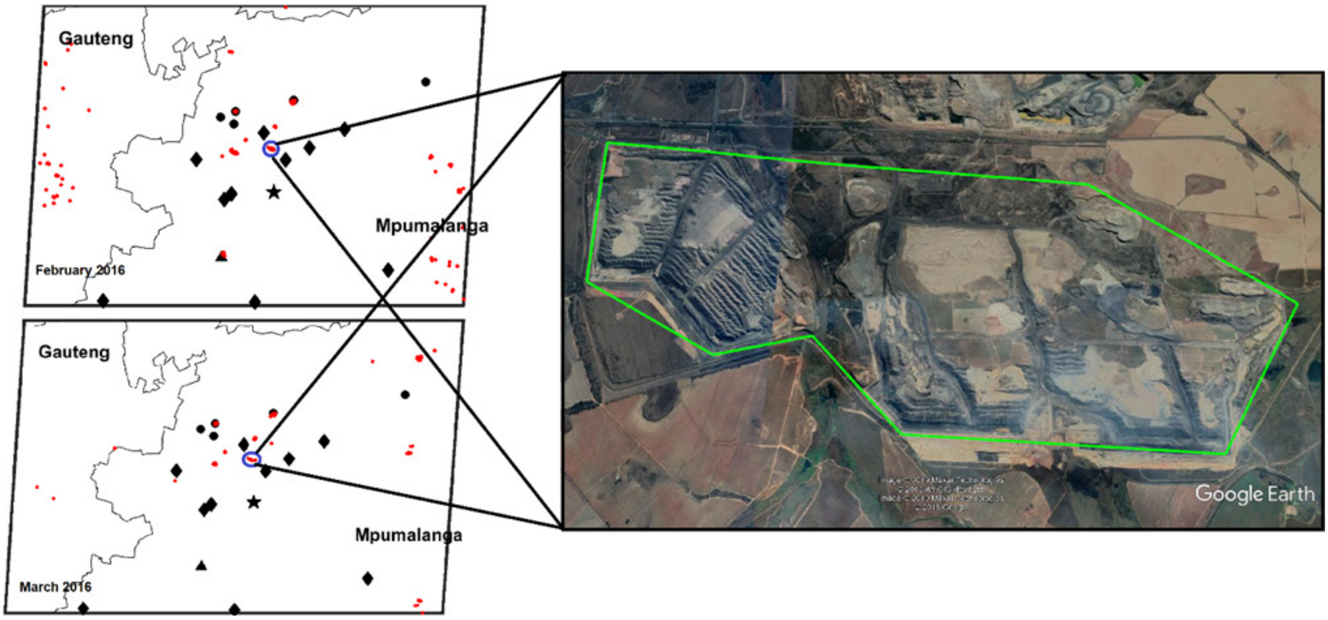

Figure 2: *Maps depicting active fires (red dots) for February (top panel) and March 2016 (bottom panel) in the Mpumalanga Highveld. Black dots (pyrometallurgical smelters), triangles (petrochemical operation) and diamonds (coal-fired power stations) indicate industrial facilities. Star indicates Elandsfontein measurement station. The blue circle indicates the 4 km by 8 km area presented enlarged in the Google Earth image.*

does not coincide with the South African interior's open biomass burning season. The green polygon seen in the Google Earth image in Figure 2, which is located within the encircled area indicates the location of an open-cast coal mine. Considering the timing (within the rainy season), reoccurring nature of the fires and that there are no clear visible signs of burnt vegetation, it is evident that the coal combustion is responsible for the observed FRP.

To investigate if there was active burning at coal mining sites, circles with radii between 1-5 km (depending on size of mining activity, determined by the above ground visible mined area) were drawn around the coordinates of each of the mining locations indicated Figure 1 and the monthly fire counts within these polygons were tallied. If reoccurring fires for consecutive months were observed, such a site was classified as having had actively burning coal.

Hysplit dispersion model

A Hybrid Single-Particle Langrangian Integrated Trajectory (HYSPLIT) dispersion calculation (Stein et al. 2015; Rolph et al. 2017) was used in the case study presented in section 3.2. The model was run on the interactive web system available at the Air Resources Laboratory website (https://www.ready.noaa.gov/index.php). The model uses particle or puff approaches to compute dispersion, trajectories or deposition. Dispersion calculations requires meteorological data as input, which can be obtained through ARL and the Global Data Assimilation System (GDAS1) meteorological dataset was used for the HYSPLIT dispersion calculation in this article.

Elandsfontein atmospheric monitoring station

The Elandsfontein atmospheric measurement station is located on a hilltop at the following coordinates 26° 14'43 S, 29° 25'30 E, 1750 MAMSL in the Mpumalanga Highveld. The surrounding environment of the Elandsfontein site is mainly grazed grassland (Mucina and Rutherford, 2006 and cultivated. No large point sources occur within a 15 km radius of the station. However, within a 100 km radius, several coal-fired power stations, pyrometallurgical smelters and a large petrochemical operation are situated (Collett et al., 2010; Laakso et al., 2012).

H_2S, ozone (O_3), nitrogen oxides (NO_x) and SO_2 were measured using a Thermo Electron 43A with a Thermo Electron 340 converter, a Monitor Europe ML9810B O_3 analyser, Thermo Electron 42i NO_x analyser and a Thermo Electron 43C SO_2 analyser, respectively. Equivalent black carbon (eBC) (definitions according to Petzold et al., 2013) was measured with a Thermo Scientific model 5012 multi-angle absorption photometer (MAAP), for which eBC concentrations were corrected according to the algorithm presented by Hyvärinen et al. (2013). In addition to the above, many other measurements were taken at the Elandsfontein station, but these measurements were not used in this paper and are therefore not discussed.

Results and discussion

Spontaneous combustion activities

Five sites recorded long-lasting and reoccurring anomalous thermal values in the FRP time series, indicating significant spontaneous combustion events. However, it is possible that sites, where combustion occurs at smaller quantities and FRP remains below MODIS detection limit could be missed. On the other hand, emissions scale with FRP (e.g. Sofiev et al., 2009) and so we consider the five sites identified here as the most important ones from air quality perspective. The locations of these sites are presented in Figure 3. All of these mines are opencast mines, which are situated above old bord and pillar mines from the 1900's. Once the roof of these underground board and pillars are opened, an influx of oxygen can cause the old unmined coal pillars to spontaneously combust (Bell et al. 2001; Pone et al. 2007).

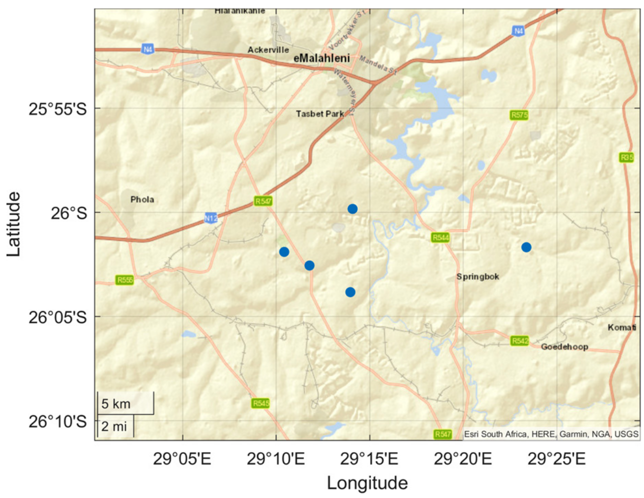

Figure 3: *Street map plotted with MATLAB indicating the positions of the five mining sites that exhibit the most spontaneous combustion events.*

The algorithm developed by Beukes et al. (2018) was applied to the repetitive fires to establish when the sites were actively burning. 3-Month moving averages of the fire pixels were calculated for each of the sites, which was then divided by the 75th percentile for that specific site (Beukes et al. 2018). These values were converted to percentages and grouped into five ranges as follows (Beukes et al. 2018):

1. Percentages ≤ 10% represented zero calculated spontaneous combustion
2. 10% > percentages ≤ 25% represented 10 to 25% of the time considered as having spontaneous combustion
3. 25% > percentages ≤ 50% represented 25 to 50% of the time considered as having spontaneous combustion
4. 50% > percentages ≤ 75% represented 50 to 75% of the time considered as having spontaneous combustion
5. 75% > percentages ≤ 100% represented 75 to 100% of the time considered as having spontaneous combustion.

The aim of considering percentage ranges of the considered time, instead of absolute percentage values is to minimize the effect of missing observations due to e.g. cloud cover over the area.

In Figure 4 the calculated percentage spontaneous combustion ranges for the five mining locations are presented. It is evident from the figure that spontaneous combustion at these 5 sites were prevalent throughout the 19-year period with locations A and B being the most active. Burning at locations A and B continued for several consecutive months, over many years. From this figure a possible season cycle also becomes evident, but this (the season cycle) will be considered in greater detail later.

In Table 1 the percentage of months with at least one active fire pixel is presented for each of the five mining sites considered. Site B was by far the most active, as on 86 % of all months there was at least one active fire within the area defined for this specific site, over the 19-year period. Site A had the second highest percentage with 59 %. Thereafter, sites E, C and D had percentages of 22, 9 and 7 %.

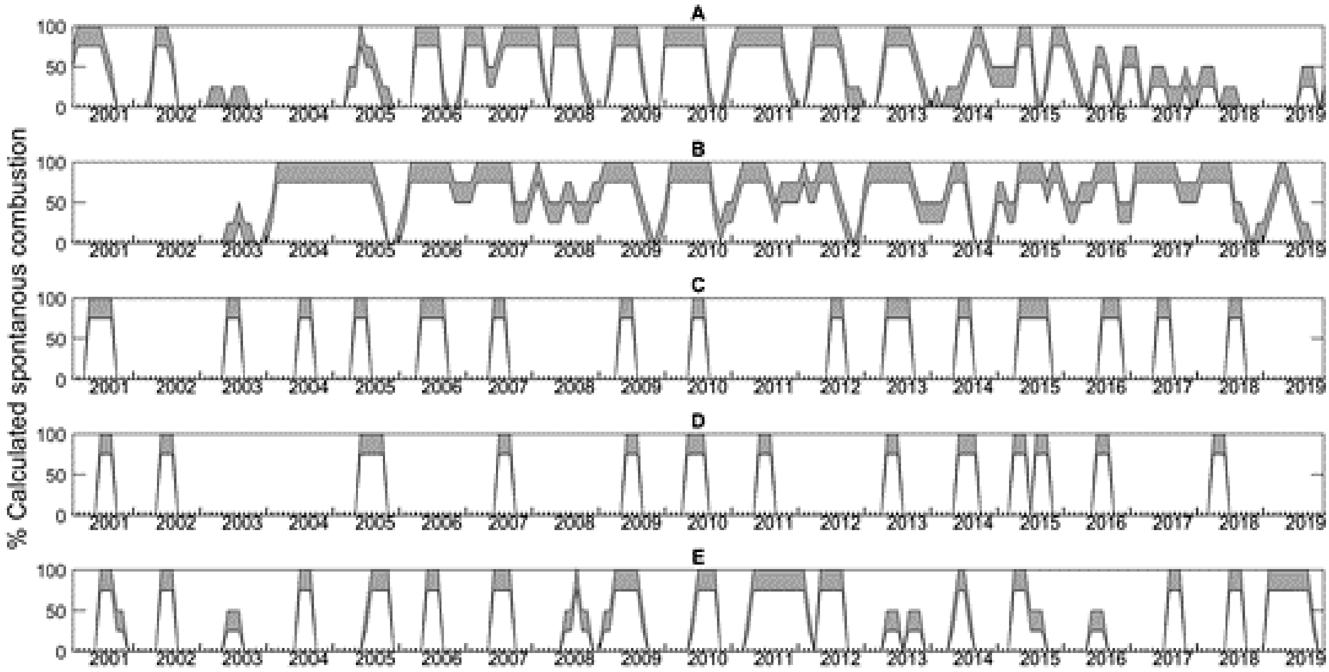

Figure 4: *The calculated percentage ranges of spontaneous combustion events for January 2001 to December 2019 for the five mining sites indicated in Figure 3.*

***Table 1:** Calculated percentage of months with at least one active fire pixel for each of the five mining sites considered.*

Site	Percentage of months with at least one burning pixel	Maximum number of active pixels per month
A	59 %	28
B	86 %	83
C	9 %	3
D	7 %	3
E	22 %	36

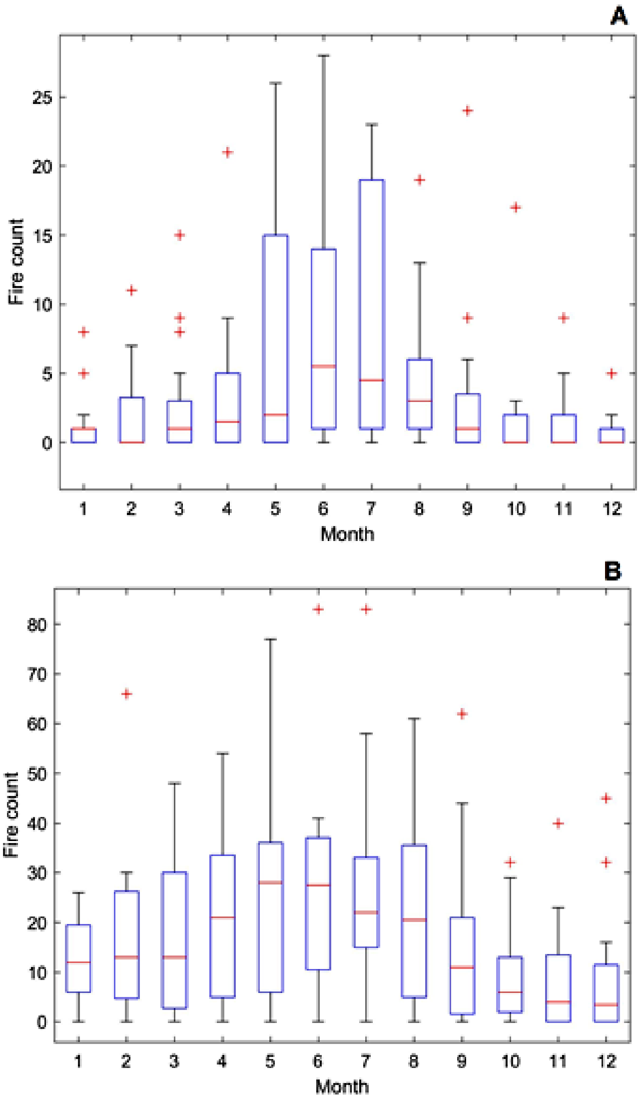

***Figure 5:** Box plots for coal mining sites A and B, which were the most prominent regarding spontaneous combustion of coal. The red line indicates the median, the top and bottom edges of the box the 25 and 75% percentiles and the black whiskers 1.5 times the interquartile range from the bottom or top of the box.*

In Figure 5 the active fire counts for site A and B are presented in a monthly box plot. From the figure it is evident that there is a relatively well-defined seasonal pattern in recorded burning activities, with burning more prevalent during the colder and drier months. Although this pattern coincides with the open biomass burning season in the South African Highveld (e.g.

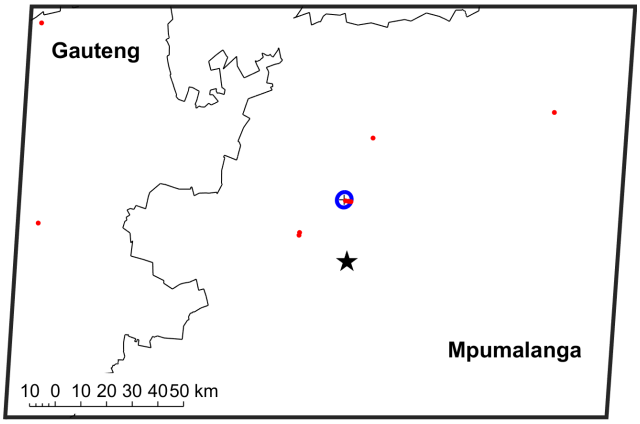

***Figure 6:** Active fire pixels (red dots) plotted from MODIS FRP data for the 22nd to the 23rd of April 2009. The blue circle represents a opencast coal mine and the black star is the Elandsfontein station.*

***Table 2:** Parameters used for HYSPLIT dispersion calculation*

Pollutant	Unspecified
Release quantity	1 mass unit
Release frequency	Continuous
Meteorology	GDAS1

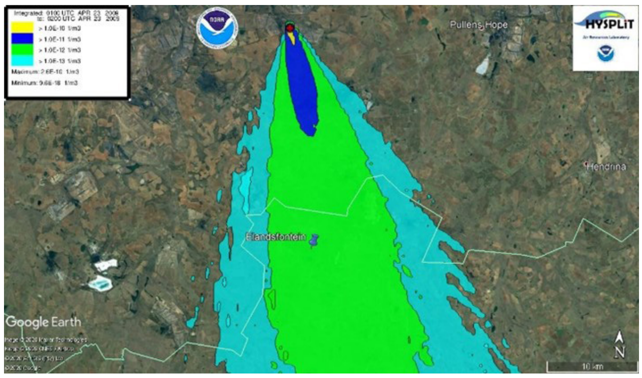

***Figure 7:** HYSPLIT dispersion calculation displayed on a Google Earth map for spontaneous combustion site B for the 23rd of April 2009 (01:00-02:00).*

Maritz et al. 2019), open biomass burning is unlikely the cause for significant increases in burning for the specific coal mining sites considered, as it is impossible for the same natural area (savannah/grassland) to burn multiple times in one month and for consecutive months. A possible cause for this observed seasonal variation could be the moisture content present in the coal. It has been found that the moisture content of coal could increase or decrease the probability for coal to self-heat and spontaneously combust (Bhat and Agarwal 1996; Xu et al. 2013). If the coal is saturated with moisture, a negligible rate of oxidation occurs and self-heating of the coal is not possible (Bhat and Agarwal 1996). However, when the coal dries during the drier months, the condensation of moisture releases latent heat associated with vaporization, which raises the heat of the coal particles and increases the potential for spontaneous combustion (Bhat and Agarwal 1996), thus the coal will be more likely to self-heat and spontaneously combust during the drier months as little to no rainfall will be occur.

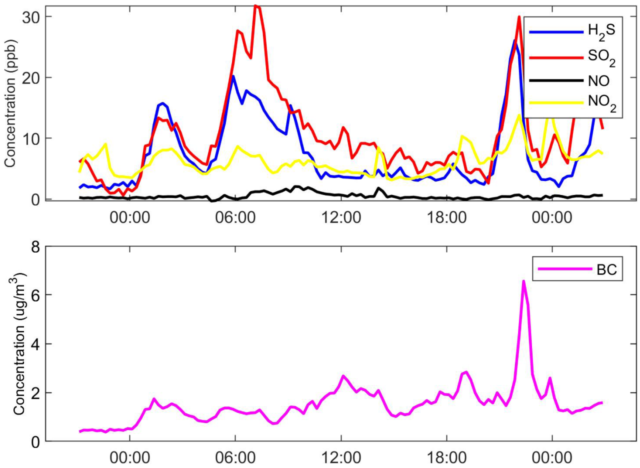

Figure 8: *Hourly concentration of trace gases and eBC measured at the Elandsfontein measurement station on the 23rd of April 2009.*

Case study of emissions originating from a spontaneous combustion event

Considering the extended time and repetitive nature of the spontaneous coal combustion fires considered in this paper, these events will emit substantial amounts of atmospheric pollutants. To illustrate this a case study is presented of a plume originating from one such spontaneous combustion event, which was measured at the Elandsfontein measurement station in the Mpumalanga Highveld. In Figure 6 active fire pixels for the burning activity under investigation is presented. On the 22nd – 23rd of April 2009 a total of 3 fires were recorded within the blue circle in Figure 6, the blue circle is representative of the opencast coal mine used in this case study.

In Figure 7 a HYSPLIT dispersion calculation (Stein et al. 2015; Rolph et al. 2017) is presented for mining site B on the 23rd of April 2009. The model was set to run from the 22nd of April at 23:00 for 24 hours with parameters displayed in Table 2.

As is evident from the dispersion calculation in Figure 7, pollutants released by the case study spontaneous coal combustion event passed over the Elandsfontein atmospheric measurement site. Figure 8 represents the hourly concentrations of trace gases (NO, NO_2, SO_2 and H2S), as well as eBC measured here, on the 23rd of April 2009. As is apparent, an increase in all species except NO is observed from 00:00, which reaches a peak at about 02:30 and decreases till 05:00. The increase in ambient trace gas and eBC concentrations are observed at the same time as the HYSPLIT dispersion calculations determined that the polluted air parcel from the spontaneous coal combustion source would reach the measurement station. Other peaks, after 05:00 in Figure 8, are also evident, but these are not discussed in this paper, since the authors will publish a full source apportionment study of trace gases measured at Elandsfontein within the foreseeable future. Considering Figures 6 to 8, it can be stated that substantial amounts of NO_2, SO_2, H_2S and eBC were released by the spontaneous coal combustion event, as H_2S and SO_2 were in excess of 10 ppb, approximately 23 km downwind of the source.

Conclusions

From this study it is evident that spontaneous combustion of coal in the Mpumalanga Highveld has a large environmental impact especially on air quality. Through the use of FRP data it was found that five mining sites were prone to spontaneous combustions over a period of 19 years. These sites were all opencast mines, situated on top of old bord and pillar mines. Of these five sites, two (A and B) were actively burning almost continually for the whole study period. A relatively well-defined seasonal pattern was observed for the spontaneous combustion activities, which were attributed to the suppression of such events during the rainy season. A case study pollution plume originating from a spontaneous coal combustion event, captured at the Elandsfontein measurement site, recorded high concentrations of NO_2, SO_2, H_2S and eBC originating from location B. Source apportionment of the contribution of spontaneous coal combustion in comparison with other sources is currently ongoing and the authors hope to publish that within the foreseeable future.

The FRP-based method we used here, demonstrates that remote sensing observations can be utilised to determine when there is spontaneous coal combustion at a site and can be applied throughout the world if the locations of mining activities is known. Furthermore, it offers a way to incorporate the emissions in air quality models (see e.g. Sofiev et al. 2009), once the emission factors have been quantified. However, the resolution of the MODIS instrumentation and frequency the satellite passes over an area might be limiting in detecting smaller combustion events.

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